ISSN 1742-1705 Volume 26 Number 4 December 2011

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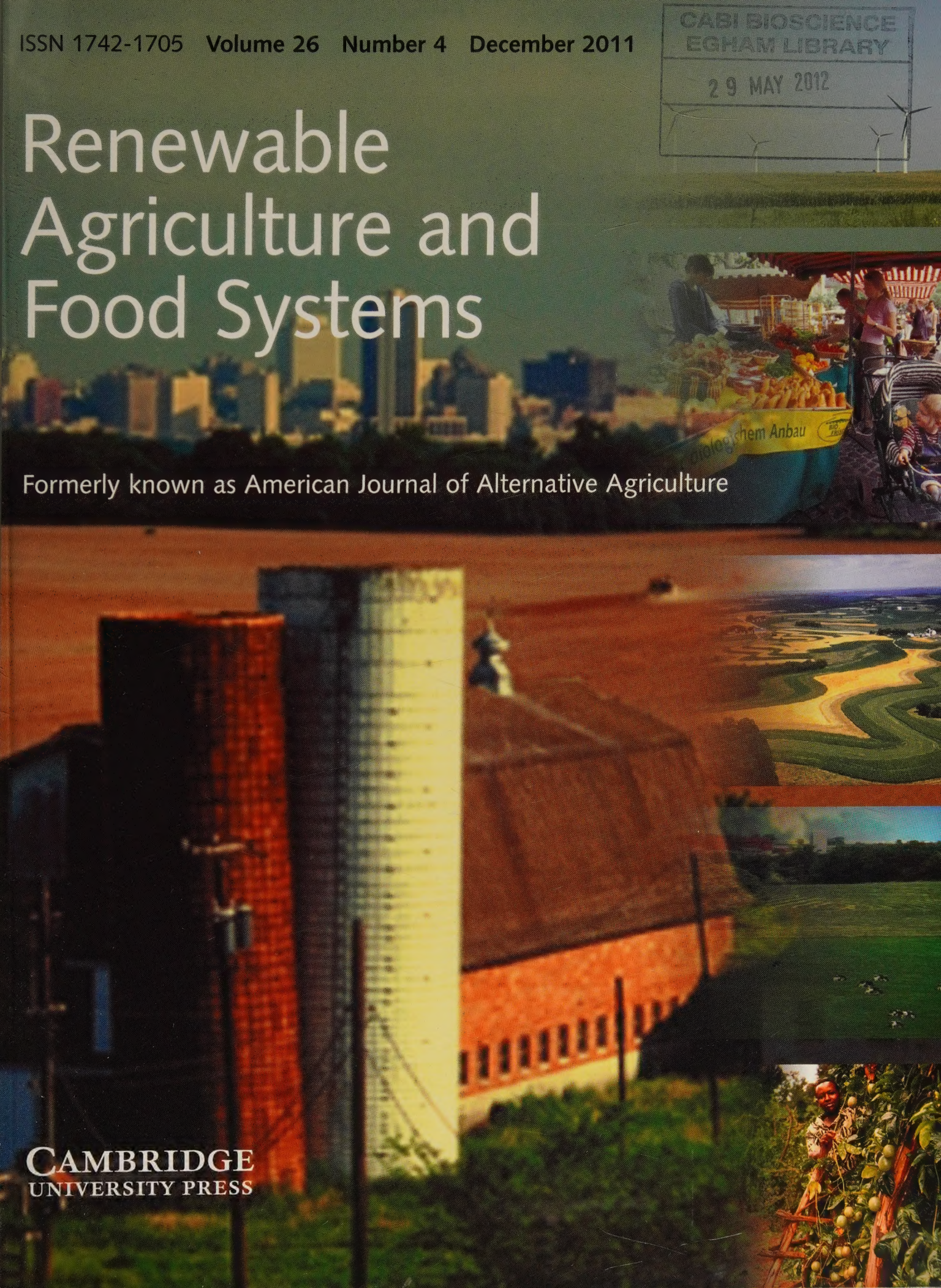
Renewable Agriculture and Food Systems

Formerly known as American Journal of Alternative Agriculture



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Renewable Agriculture and Food Systems (ISSN 1742-1705) is published four times a year in March, June, September and December. The subscription price for institutions of Volume 26 (2011) which includes electronic access and delivery by air is £203 (US $400 in the USA, Canada and Mexico); the electronic only price for institutions is £152 (US $294 in the USA, Canada and Mexico). Single parts are £57 (US $100 in the USA, Canada and Mexico), plus postage.

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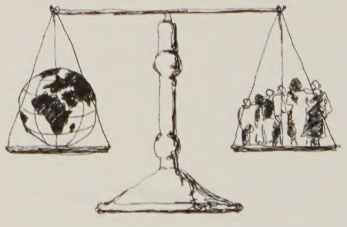

"Sustaining Earth and its People"

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Renewable Agriculture and Food Systems: 26(4); 267–268 doi:10.1017/S1742170511000421

Parting editorial: Renewing Earth and its people – translating science into practice

With some regret I announce my retirement as Editor-in-Chief. Over the past decade, *Renewable Agriculture and Food Systems* (*RAFS*) has broadened the original scope of its predecessor, *American Journal of Alternative Agriculture*. We strongly encourage publication of practical and integrated, biologically based systems approaches that meet the challenges of social and economic change, dwindling natural resources and climatic instability in achieving the global vision of 'Renewing Earth and its people' with a focus on 'Translating science into practice'.

Renewable Agriculture and Food Systems stands apart from other journals in its field. Its unique nature, recently tabulated by a polling of Associate Editors and practitioners around the world, include the following:

International breadth: with increasing numbers of contributions from three global regions: Asia/Australasia, Eastern Europe/Middle East/Africa and North/Central/South America.

Emphasis: a focus on biologically based integrated systems approaches, including rural/urban agricultural sociology, and focus on food systems issues.

Multiple content categories: including original peer-reviewed Research papers and Review articles, Preliminary reports, Forum, Commentaries, and Book reviews. The journal occasionally publishes themed issues.

Efficient review process: leading generally to decisions on manuscripts within 2–3 months after submission and online publication 4–6 weeks after acceptance.

Promotion of participatory interactions: with practitioners through coverage of a wide range of topics of interest to them, using less technical jargon, and providing practical, workable applications and solutions aimed at increasing sustainability.

Themed issues: often co-edited by Associate Editors, focus on specific topics to broaden understanding beyond contemporary agriculture to include renewable agricultural systems that contribute to a sustainable future. Examples include: Perennial grain crops (Volume 20 Issue 1); Soil quality for sustainable management (Volume 21 Issue 1); Meeting food and resource needs: Organic agriculture and the global food supply (Volume 22 Issue 2); Researching sustainable agricultural systems, ISOFAR 2005 (Volume 23 Issue 1); Principles of integrated agricultural systems (Volume 23 Issue 4); Food for life: Looking beyond the horizon (Volume 25 Issue 1); Sustainable agricultural systems in a resource limited future (Volume 25 Issue 2).

In 2012 (Volume 27), a themed issue on Conservation tillage strategies in organic management systems will highlight the differences in degree and nature of reduced tillage in organic management systems between Europe and North America due to differences in climate, soils, economic, social and cultural issues.

Forum: this provides a discussion section for researchers, farmers and others, to encourage focused dialog, on often controversial topics, with widely divergent viewpoints. The most controversial and widely visited Forum discussion was 'Can organic agriculture feed the world?' by Badgley and Perfecto[1] which included detailed criticisms from a renowned scientist and a progressive Great Plains farmer. A scathing Commentary on. '"Organic abundance" report: Fatally flawed' by Alex Avery[2] and Responses to it were published two issues later in December 2007.

Preliminary reports on highly innovative systems: these cover areas about which little prior research has been done but which show promise for development into highly valuable and exciting renewable management systems. One example, a report on floating gardens in Bangladesh by Irfanullah et al.[3], used water hyacinth weeds that were hazards to navigation in river channels to build floating gardens in bordering wetlands—thus helping to remediate problems of nutritional security and lack of arable land accessibility in coastal villages where rising sea levels threaten human activities and livelihoods.

I would like to extend thanks to our outstanding and dedicated group of Associate Editors and the many reviewers who provided timely, substantive and insightful reviews over the past decade. Your efforts have resulted in a quality journal with timely publication. A special recognition is given to Valerie Dennis, our 'miracle worker' editorial office manager, whose efforts have greatly facilitated the timely review of manuscripts and provided needed guidance and relief from intermittent frustrations with 'electronic' editing. Gratitude is also extended to the journal support staff of the Henry Wallace Institute of Alternative Agriculture, CABI and, most recently, Cambridge University Press for outstanding support in publishing the journal. One indication of the journal's advancement is the almost tripling of the Impact Factor between 2005 and 2009. A special thanks to three Associate Editors who are retiring with me at the end of 2011: Molly Anderson, College of the Atlantic, Maine USA, for her 20 years of service as an Associate Editor and contributions to sustainable food systems; Mark Liebig, USDA-ARS Soil Scientist at the Northern Great Plains Research Center, for his inspiration to me as my 'professional' son and his 9 years' service as an Associate and Forum Editor; and last but not least to John Ryan, internationally renowned dryland soil specialist, ICARDA/CGIAR, Syria for his 9 years' service as an

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Associate Editor and his patience in listening to outlandish visions from this fellow Irishman.

I recognize the pioneering efforts of former Editors:

Garth Youngberg, a visionary before his time, for founding and defining the vision of *American Journal of Alternative Agriculture* and in blazing a trail through the forest of political, social and professional opposition to the notion that the continued adoption of agricultural technologies relying heavily on fossil fuel energy, capital and chemical inputs was not environmentally or economically sustainable.

Dr William Lockeretz, for his commitment and role as Editor and Technical Editor, over a 12-year period, which documented the history and helped promote the viability of organic agriculture as a sustainable alternative to chemically intensive industrial agriculture (see Volume 23 themed issue 1, Researching sustainable agricultural systems, ISOFAR 2005; and the Volume 25 Issue 1, Book review of Organic Farming[4]).

Dr Robert Papendick, Soil Scientist, Pullman, Washington for his 5 years service as Editor of *American Journal of Alternative Agriculture* and his contributions to maintaining the credibility and high caliber of the journal and in emphasizing the importance of the quality of soil resources in maintaining sustainable food production and food and environmental health.

A special recognition to **Charles 'lightning' Francis** who has served as an Associate Editor from the beginning, recently serving as Resources Review Editor and in essence as a Co-Editor-in-Chief through numerous consultations, Commentaries, Editorials, and for his amazing capacity to digest and succinctly summarize large amounts of information in a short period of time.

I hope that this editorial has done justice to those that came before me in my quarter century of service to the journal. The journal name and cover were changed in 2004 because the journal had emerged to the point where the systems it was promoting were no longer merely 'alternatives' to conventional agriculture, but solutions to sustainability. The journal continues to provide a common ground where scientists, educators, policy makers, environmentalists, farmers, community organizers and other practitioners of various perspectives can share their research and ideas for affirming Renewable agriculture and food systems that meet people's needs and restore the productive capacity of the Earth. In my tenure as Editor-in-Chief, and my career as a scientist, my personal goal has been to 'translate science into practice' by creating tools and approaches for building soil health and renewing an agriculture/social system that would help us flourish in this new millennium through re-forging partnerships with all of society and the natural world that supports us. My vision for practical science and foundation for scientific concepts was nurtured by several 'people of the land' such as George Tasker, my father-in-law, timberman and self-educated ecologist from the Appalachian Mountains of Virginia; farmers and futurists Dick and Sharon Thompson, Fred Kirschenmann and Wes Jackson from America's heartland; and John Jeavons for his development of Grow Biointensive Agriculture[5] that is meeting basic soil, food and people's needs in over 100 countries and urban sites around the world.

A special thanks to my wife and life partner, Janet, who kept the home fires burning and cared for our daughter Karin while I traveled the world, in co-founding with me the Renewing Earth and Its People Fund (www.reapfund.org) and for patiently serving as my first Editorial Assistant for the journal.

I welcome the new Editor-in-Chief Rick Welsh, Professor of Sociology, Clarkson University, NY, USA and his assistant Lydia Oberholtzer, a Senior Researcher with Pennsylvania State University. They not only bring a new sociological strength to the journal but also maintain our historical connection with the Henry A. Wallace Center for Agricultural and Environmental Policy at Winrock International. Rick and Lydia have met with Cambridge University Press to discuss future plans for changes needed to maintain the scientific excellence and practical significance of *Renewable Agriculture and Food Systems*. Seeking to support the global expansion of the journal, the new Editors and Cambridge University Press will explore ways to assist authors from developing and other countries, for which English is not their primary language, to submit reports on unique and innovative food production systems for consideration of publication in the journal.

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John Walsh Doran
Editor-in-Chief, *Renewable Agriculture and Food Systems*

Co-Founder, Renewing Earth and Its People
(www.reapfund.org)

Professor and Scientist Emeritus, University of Nebraska
and USDA-ARS, Lincoln, NE, USA.
doranrafs@gmail.com

Renewable Agriculture and Food Systems: 26(4); 269–275 doi:10.1017/S1742170511000184

Controlled studies further the development of practical guidelines to manage dodder (*Cuscuta gronovii*) in cranberry production with short-term flooding

James M. O'Connell[1], Hilary A. Sandler[1,*], Lynn S. Adler[2], and Frank L. Caruso[1]

[1]University of Massachusetts Amherst Cranberry Station, East Wareham, MA 02538, USA.
[2]Department of Plant, Soil, and Insect Sciences, University of Massachusetts, Amherst, MA 01003, USA.
*Corresponding author: hsandler@umext.umass.edu

Accepted 21 March 2011; First published online 20 May 2011 **Preliminary Report**

Abstract

Flooding is an inexpensive cultural practice used for pest management in Massachusetts cranberry (*Vaccinium macrocarpon* Ait.) production. This project examined the use of short-term floods (<72 h) for dodder (*Cuscuta gronovii* Willd.) management under controlled conditions. Using incubators, seed was submerged in water for 0, 24 and 48 h at 10, 15 and 20°C (simulating spring water temperatures) and 0, 12, 24, 36 and 48 h at 15, 20 and 25°C (simulating summer water temperatures). Two 1-year controlled studies (field and greenhouse) evaluated three flood durations (0, 24 and 48 h) and four flood initiations (1, 2, 3 and 4 weeks after early seedling emergence (AEE)). Treated seeds were planted to cranberry vines and to Petri dishes; percent germination, degree of dodder attachment and dodder biomass data were collected. Treatments had limited effect on seed germination. Flooding 4 weeks AEE resulted in the lowest mean attachment ratings and dodder stem biomass on cranberry. This preliminary work provides evidence that flooding may retard dodder stem growth rather than reducing seed germination and that floods initiated after some time has elapsed after early emergence may be more effective than those initiated closer to the time of seedling emergence. More information is needed to thoroughly understand the processes involved; however, small projects such as this can provide interim guidelines that growers can immediately consider when deciding on a dodder management program.

Key words: non-chemical weed control, parasitic plants, flooding, cultural practices, integrated weed management

Introduction

The American cranberry (*Vaccinium macrocarpon* Ait.) is indigenous to North America and is closely related to the small cranberry (*Vaccinium oxycoccus* L.) and the lingonberry (*Vaccinium vitis-idaea* L.), which are found throughout Europe, Asia and parts of North America[1]. It is a low-growing, slender, vine-like woody perennial that can remain commercially productive for decades. It produces short vertical branches (uprights) 5–20 cm in height and long prostrate branches (runners) from 1 to 2 m in length[1]. Runners colonize the open soil, while the uprights produce reproductive and vegetative buds.

Dodder (*Cuscuta gronovii* Willd.), an obligate parasite characterized by slender, thread-like yellow–orange twining stems, is a serious pest in cranberry. A recent survey indicated that 45% of cranberry growers reported that 5–25% of their farms are typically infested with dodder; one-third reported that more than 50% of their farms can be infested in any given year. Dodder was ranked as either first or second as a problematic weed by 25% or 20% of growers surveyed, respectively[2]. Its vigorous growth habit, combined with a prodigious[3] and long-lived seed bank, makes management difficult. Although *Cuscuta* spp. may overwinter as haustoria in host stems[4,5], the seed bank is likely the main contributor leading to new infestations in any given year. Thus, limiting seed production is seen as the critical link in the life cycle (Fig. 1) that must be broken to make any significant gains in management of this pest. When parasitism is successful, dodder can have multiple attachments that create a dense mat reducing the amount of light penetrating into the plant canopy. Light reduction,

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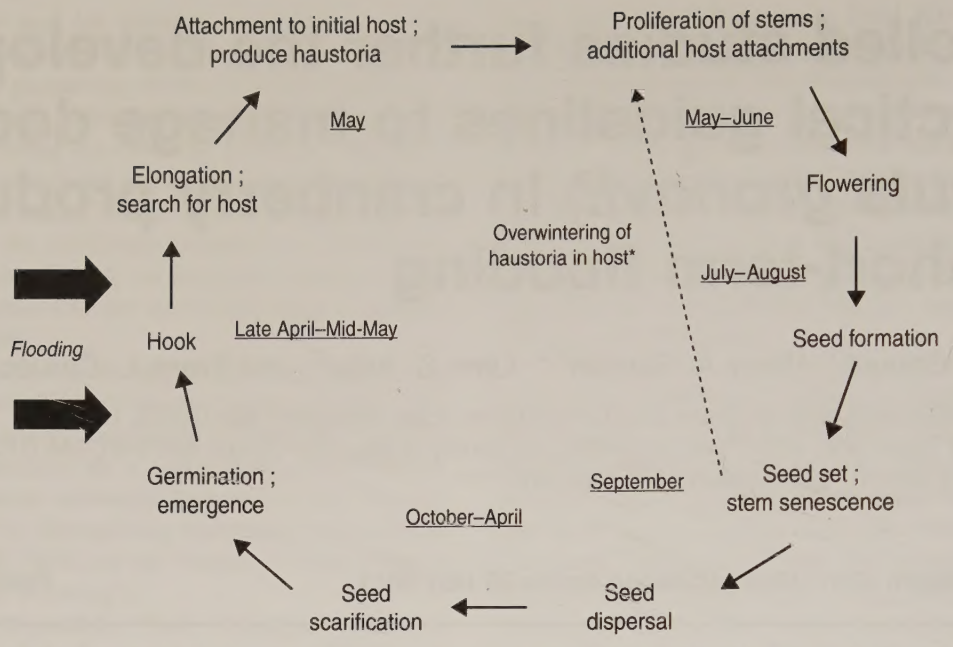

Figure 1. Model of the life cycle of dodder. Calendar dates are related to typical conditions for Massachusetts. *May occur in some dodder species.

combined with the removal of water and nutrients from the cranberry vine by the haustoria, can cause cranberry yield losses as high as 80–100%[6].

Chemical herbicides are the primary tools available to cranberry growers for dodder management[7]. Growers routinely scout for early emerging seedlings to time pre-emergence herbicide applications. Even when these applications are timed properly, extended periods of dodder seedling emergence[8] can result in escapes that require additional management. Post-emergence control options include raking[9], hand-pulling and the application of household cleaning products[10]. Glyphosate applications, though effective in alfalfa[11], are not a viable option because the herbicide will injure cranberry[12,13].

Flooding is an important management tool used by cranberry growers to protect plants from winter injury[14] and to manage insect pests[15]. Growers may use multi-week spring or fall floods to manage cranberry fruitworm (*Acrobasis vaccinii* Riley), fruit rot and dewberries (*Rubus* spp.)[16,17]. They may also use short-term (48-h) floods in mid-May as a management option for black-headed fireworm (*Rhopobota naevana* Hubner)[18]. Temperature is an important criterion as water that is too warm can negatively impact stored carbohydrates in cranberry and reduce yields[19]. Whether used deliberately or accidentally, flooding is known to impact weed species. In rice (*Oryza sativa L.*) cultivation, flooding for several weeks reduced plant height and inhibited seedling emergence for two species of morning glory (*Ipomoea wrightii* Gray and *Ipomoea lacunose* L.)[20], a close relative of dodder. Germination of texasweed (*Capernoia palustris* (L.) St.-Hil.) was inhibited, while the soil was constantly saturated or flooded 10 cm above the soil surface, but floods had no effect on the survival of texasweed at any emergent growth stage when compared with the untreated control[21]. Demonstration-style studies that evaluated flooding as a management tool for dodder in cranberry produced varied results[22]. Controlled studies have not been conducted to determine the best methodology for the use of flooding for dodder management in cranberry.

The focus of this research was to build on observations from previous demonstration studies to further develop practical recommendations for the use of short-term floods (24–48 h) as a management tool for dodder in cranberry. When should the flood be applied and for how long? Is water temperature important? Utilizing a routine scouting technique as a trigger for treatment, our objective was to determine the effect of water temperature, flood duration and timing of flood initiation on dodder seed germination, the degree of attachment of the parasite to the host and the fecundity of the parasite.

Materials and Methods

Dodder seed collection and preparation

Dodder seed was collected from a commercial Massachusetts cranberry farm (41°47′N, 70°40′W) in 2005. Plants showing evidence of copious dodder seed production were identified, pulled out of the ground and placed into large paper bags. Once at the lab, all biomass was stored at 21°C and allowed to air-dry. Within 3 weeks, dodder seed capsules were separated from the host, placed onto a fine mesh sieve (US Standard Sieve, Sieve No. 100, 150 µm) and crushed repeatedly by hand to separate the seed from the capsules. Gentle shaking of the sieve separated the

seeds from any remaining chaff. Using a dissecting microscope, healthy seeds (i.e., yellow in color, fully spherical in shape) were visually sorted from damaged seeds (i.e., off-color and misshapen); the former were placed in glass scintillation vials and stored at 21°C until needed.

Dodder seed was scarified in concentrated sulfuric acid (36.8 N, Fisher Scientific, Pittsburgh, PA) to break dormancy[23] with a soak time of 15 min. The seeds were then rinsed for 1 min in sodium hydroxide (2.5 N, Fisher Scientific, Pittsburgh, PA) and then rinsed for 1 min in deionized water. Once dried, seeds were counted and weighed. The average seed weight was determined from weighing four separate batches of 100 seeds. Once weighed, the allotment of seeds was placed into cloth pouches (as described below). One hundred seeds (as determined by weight) per pouch were used in water temperature studies, and 200 and 100 seeds for the 2006 and 2007 flood initiation studies, respectively. The decision to use fewer seeds in the 2007 studies was due to logistics.

Water temperature and flood duration studies

Incubator studies were designed to evaluate the effect of water temperature on dodder seed germination. To simulate spring conditions in Massachusetts, three water temperatures (10, 15 and 20°C) were evaluated. To evaluate the use of short summer floods for post-emergence dodder control, slightly higher temperature levels (15, 20 and 25°C) were used. These temperatures represent a reasonable range of temperatures for flood waters on cranberry farms in spring and summer conditions in Massachusetts[24]. For both experiments, seeds were placed into 10×10 cm cotton pouches that were stitched on three sides. The top was folded over twice and stapled shut to prevent seed loss. Pouches subjected to spring and summer water temperatures were submerged for 0, 24 or 48 h and 0, 12, 24, 36 and 48 h, respectively. Shorter retrieval intervals were used in the latter case since the risk of injury for flooded vines is higher under summer conditions[19,25]. Both experiments were repeated twice.

Four incubators (Fisherbrand, Model 146E, Pittsburgh, PA) served as replication units for both experiments, each of which was conducted over a 3-week period. Each week, all four incubators were set to the same temperature and monitored with a standard thermometer. The effect of week on the results cannot be entirely disregarded since one temperature treatment was tested each week (i.e., 10°C in week 1, 15°C in week 2, etc.). A single water-filled 19-liter plastic container was placed inside each incubator and allowed to thermoequilibrate at each temperature level for at least 24 h before submerging seeds. Thermometers were placed in the interior of the incubator and in the water-filled containers to verify that the desired temperatures were reached. Seeds in pouches representing the 0 h treatment were transferred directly to Petri dishes that contained a 50 : 50 sand : peat mix. The remaining pouches were submerged and removed after 12, 24, 36, or 48 h as appropriate. Seeds from each pouch were planted as a group, with the contents of one pouch placed in a Petri dish. Seeds were incubated at 22°C in the dark for at least 3 weeks[23]. Dishes were checked at least weekly; germinated seeds were counted, removed and percent germination was determined.

Flood duration and timing studies

Vine propagation. Cranberry plants (cv. Stevens) were propagated from cuttings taken from State Bog at the University of Massachusetts Cranberry Station farm, East Wareham, MA. A method (T. Roper, personal communication) commonly used by cranberry researchers was employed for upright propagation. Sand was collected from the University of Massachusetts Cranberry Station farm in East Wareham, MA and sieved to obtain particle sizes used in cranberry production[26]. The sand was combined with sphagnum peat moss in a 3 : 1 (v/v) mix in an electric cement mixer to blend thoroughly; water was added to evenly moisten the mixture. Uprights at least 7 cm in length were cut with hand pruners from the research farm. Once cut, the uprights were kept damp at 5°C until planted. Under these conditions, the cuttings will stay viable for 1–2 weeks. Before planting, Weedblock® landscape cloth (Easy Gardener, Waco, TX) was placed in the bottom of each pot to contain the sand : peat mix. Vines were then cut to 7.6 cm lengths and leaves were removed from the bottom 5 cm. Each upright was placed into pre-made holes and filled with the sand : peat mix; no rooting hormone was used. Pots were watered as needed to encourage rooting, establishment and growth.

Incubator conditions. To simulate springtime environmental conditions in Massachusetts, seeds were submerged in water-filled plastic containers under controlled conditions inside a growth chamber (Percival Scientific, Perry, IA, Model No. PGC-10). Lights were turned on and off gradually, starting at 6.00 h and ending at 21.00 h for a 15-h day. Light levels ranged from 500 to 1000 µmol depending on distance from the lights. Night temperature was 15°C, and was gradually raised until the temperature reached 19°C at 14.00 h. The temperature was then gradually reduced from 16.00 h to 23.00 h. The growth chamber was started at least 24 h prior to treatment application to allow the water to thermoequilibrate with the surrounding environment.

Determination of biological marker. Since research indicated that peak dodder seedling emergence on cranberry bogs occurred 2–3 weeks after early seedling emergence (AEE)[8], early seedling emergence was selected as the biological marker for flood initiation (Fig. 1). Growers currently scout for early emerging seedlings to time herbicide applications[27], and so using this biological marker would be easy to incorporate into a practical plan for timing a flooding event. Containers, representing a simple system of simulated bogs, have been used to monitor the

Table 1. Percent germination of dodder seed plated to Petri dishes after being subjected to various flooding durations at various temperatures under controlled conditions in an incubator. Values are mean ($n = 8$) ± standard error.

Temperature scenario (Spring/Summer)	Flood (h)	Germination (%)	
		Spring	Summer
10°C/15°C	0	49 ± 5.0	46 ± 3.6
	12	n/a	50 ± 2.8
	24	43 ± 4.4	47 ± 2.6
	36	n/a	54 ± 2.1
	48	44 ± 3.7	48 ± 4.9
15°C/20°C	0	40 ± 2.2	48 ± 2.6
	12	n/a	46 ± 2.8
	24	47 ± 4.9	47 ± 2.7
	36	n/a	48 ± 2.4
	48	48 ± 3.2	48 ± 2.9
20°C/25°C	0	50 ± 2.9	53 ± 2.5
	12	n/a	48 ± 3.2
	24	53 ± 4.1	54 ± 3.9
	36	n/a	49 ± 2.4
	48	48 ± 3.9	52 ± 2.3

n/a = not applicable.

germination pattern of Massachusetts dodder seed for more than 11 years[8]. The start of the experiment was determined by checking for early seedling emergence in these containers. The studies were initiated on May 7, 2006 and May 15, 2007, 1 week AEE, by placing seed pouches into each bucket.

Study setup. In both years, the experiment had three flood durations (0, 24 and 48 h) and four times of flood initiation (1, 2, 3 and 4 weeks AEE). All treatment combinations were replicated five times. Prior to submersion, a portion of the seeds were planted directly (representing the 0-h flooding treatment) to pots containing rooted cranberry vines and to Petri dishes filled with the sand : peat mix. Incubation in Petri dishes was included to assess seed germination in the absence of a host. Seeds placed in pouches (as described above) were submerged in five 11-litre plastic buckets inside the growth chamber. Each bucket was filled to a depth of 27 cm and pouches were held to the bottom with a weight. As each flooding time period elapsed, pouches were removed from each bucket and the seeds were removed as a group from each pouch and planted to a pot containing cranberry or to a Petri dish. Seed germination and attachment were monitored as described below.

In 2006, after being inoculated with dodder seed, all pots were planted directly into an area of the research farm to expose treated seeds to realistic environmental field and weather conditions. The site was prepared by hand-pruning runners in the plot area, and then cultivating with a front tine, forward rotating, 23-cm width rototiller (Echo Inc., Lake Zurich, IL). Arranged in a randomized complete block design, pots were planted with the rims above the soil line (approximately 7 cm deep in the soil). The study had 5 rows of 12 pots (each row represented a block) spaced 0.5 m apart; pots were spaced 0.25 m apart. The 2007 experiment was conducted in the greenhouse. Pots were arranged in a randomized complete block design with five replicates. All plants received 1 g of Osmocote® 14-14-14 slow-release fertilizer in early May. All plants were watered as needed.

Collection of germination, attachment and biomass data. Petri dishes containing dodder seeds were placed in an incubator at 22°C and checked weekly for seedling emergence. Germinated seedlings were counted and removed for at least 3 weeks, and germination percentage was determined.

Following inoculation with dodder seed, all pots were visually rated weekly for dodder infestation. A qualitative rating scale of 0–4 was used to assess the degree of dodder attachment to its host. A rating of 0 indicated zero attachments, a rating of 1 indicated less than 3 attached stems (scarce), a rating of 2 indicated 4–6 attached stems (few), a rating of 3 indicated 6–10 attached stems (moderate) and a rating of 4 indicated more than 10 attached stems (heavy). The experiments were maintained for 6 months (May–October) in each year.

Cranberry and dodder biomass and dodder seed were collected, October 27–30, 2006 and October 24, 2007. The vines were cut at soil level using hand pruners, one replicate at a time. Cranberry biomass, dodder biomass and dodder seed were separated and placed into individual paper bags. Cranberry biomass was dried at 60°C for at least 2 days, and the dry weights recorded. Dodder biomass and seeds were allowed to air-dry prior to recording their weights. All seeds collected were tested for germination as described above.

Statistics. All data were analyzed in SAS version 9.1 (SAS Institute Inc., Cary, NC). Germination data were checked for normality and no transformations were needed. All germination data were analyzed in Proc Mixed with blocks (replicates) nested within repetition. Data for dodder biomass (dodder stem and seed) and total number of dodder seeds produced were analyzed using Proc GLM. Attachment ratings were categorized as ordinal response variables, which violate the assumptions of a standard analysis of variance[28]; these data were analyzed in Proc Logistic. Orthogonal polynomial contrasts were used to determine linear and quadratic relationships for significant continuous variables, and regression lines were calculated as appropriate. Mean separation for significant treatment levels was performed using Tukey's Honestly Significant Difference test at $P = 0.05$.

Results and Discussion

Water temperature and flood duration

Neither water temperature nor flood duration affected seed germination for the spring or summer scenarios (Table 1). Germination values ranged from 40 to 53% and from 45 to

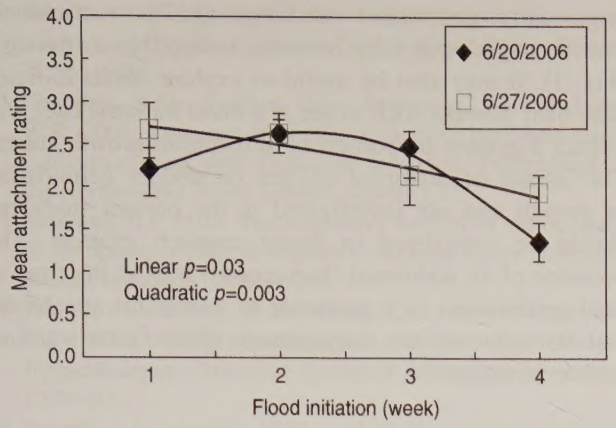

Figure 2. 2006 mean attachment rating of dodder on cranberry vines following submersion in water for a certain number of weeks AEE for June 20 and June 27, 2006. A rating of 0, 1, 2, 3 and 4 indicated 0, 1–3, 4–6, 6–10 and >10 attached stems, respectively. Bars are standard error of the mean.

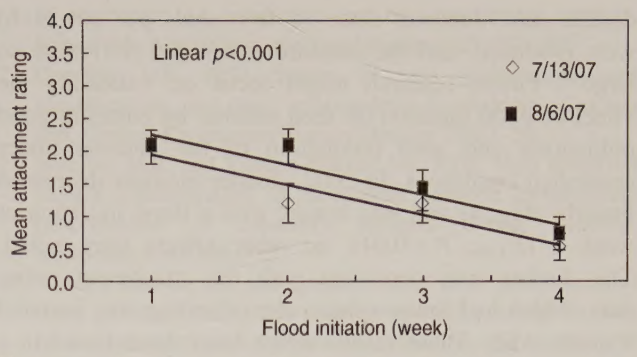

Figure 3. 2007 mean attachment rating of dodder on cranberry vines following submersion in water for 1–4 weeks AEE for several dates in July and August 2007. A rating of 0, 1, 2, 3 and 4 indicated 0, 1–3, 4–6, 6–10 and >10 attached stems, respectively. Dates of July 19, 2007, August 1, 2007 and August 28, 2007 were also significant, but are not included since dates in the figure are representative. Bars represent standard error of the mean.

53% for the spring and summer scenarios, respectively. The mean germination values fell within normal dodder germination ranges noted in previous laboratory studies (H.A. Sandler, unpublished results). When evaluated under the stated controlled conditions, flood duration and water temperature had no practical impact on seed germination. This conclusion supports previous work that found flooding reduced dodder stem weights, but did not impact seed germination[22]. The results from the incubator experiment further suggest that differences observed in the field may be attributable to impacts on emerged seedlings. This theory is supported by a study conducted on hairy beggarticks (*Bidens pilosa* L.) seedlings that showed a decrease in emergent seedlings with increased duration of flooding[29].

Flood duration and timing

Seed germination in Petri dishes. Flood duration and week of initiation affected seed germination. Weeks 1 and 4 had lower germination compared to Weeks 2 and 3 (38% versus 45%, respectively). Seeds submerged for 24 or 48 h had a slightly higher percent of germination (43%) than seeds submerged for 0 h (38%). Again, the germination rates fell within previously observed germination ranges for dodder seed. These data correspond to the trends noted in the water temperature/flood duration incubator study and support the contention that floods do not impact seed germination.

Attachment rating. Mean attachment ratings in 2006 were affected by flood initiation. Mean attachment ratings for cranberry vines (Fig. 2) were lowest at 4 weeks AEE for observations recorded on June 20 ($X^2 = 14.25$; $P = 0.003$) and June 27, 2006 ($X^2 = 9.29$; $P = 0.03$). There was no treatment effect seen for July 14, 2006 or later (data not shown)[30]. The authors observed dodder senescence at this point in time.

In 2007 (Fig. 3), mean attachment rating was also lowest at 4 weeks AEE. The effect of flood initiation at 4 weeks

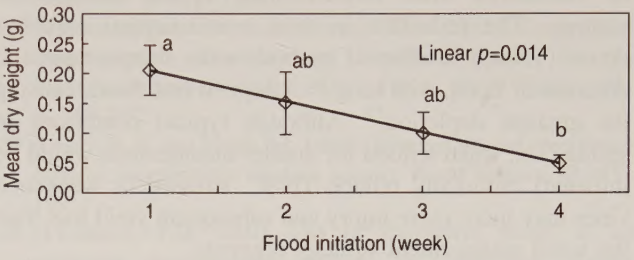

Figure 4. In 2007, mean dry weight of dodder on cranberry subjected to floods initiated 1–4 weeks AEE. Mean separation with Tukey's HSD; means with the same letter are not significantly different. Bars represent standard error of the mean.

AEE was observed for dates of July 13, 2007 ($X^2 = 13.49$; $P = 0.004$) and August 6, 2007 ($X^2 = 14.95$; $P = 0.002$). Attachment ratings were lowest at 4 weeks AEE, indicating that a later flood initiation may provide better control of dodder than an earlier flood initiation (relative to early seedling emergence). These results are supported by previous field research[22], which found that short-term floods initiated 1 week AEE had no effect on seed germination in one year (seeds placed in pouches and secured to the bog floor), while in another year, floods initiated 3 weeks AEE reduced dodder stem weights (i.e., indirect evidence that flooding later suppressed dodder infestation). Results support the premise that short-term floods affect dodder growth (i.e., biomass) and not seed germination.

Dodder stem biomass and seed number. In 2006, mean total seed number at the 48-h flood duration was similar to 0-h duration (2.2 versus 0.9 seed per pot) and both were lower than the 24-h flood duration (5.6 seeds per pot) ($F_{2,44}$; $P = 0.011$); no other effects were noted. This result is contrary to expectations since it was thought that flooding would reduce seed production (fecundity). The effects seen in the present study may not be a true description of the effect of flood duration on

dodder seed numbers since so few seeds per pot (1–6) were produced, and the standard errors (0.4–1.3) were so large[30]. Future research might focus on validating the effect of flood duration on seed number by ensuring good pollination and seed production of the parasite under controlled conditions. In 2007, dodder biomass decreased linearly (Fig. 4) and was lowest with a flood initiation at week 4 ($F_{3,44}$; $P = 0.04$); no other effects were noted. This finding was consistent with the attachment rating data, which had lower values when flooding was initiated 4 weeks AEE. These results differ from those found in a texasweed study where flooding at an earlier growth stage (2.5 cm tall plants) reduced plant biomass, but flooding at a later growth stage (7.5 and 15 cm-tall plants) did not affect texasweed biomass[21].

Although used to manage other serious cranberry pests, such as *Sparganothis sulfureana* (Clemens)[31] and black-headed fireworm[18], flooding can reduce the carbohydrate reserves in cranberry[24] and this physiological impact must be considered when implementing a pest management strategy. The reduction in total non-structural carbohydrates (TNSC) is affected by both water temperature and duration of flood, with long (>3 days) warm floods causing the greatest depletion[19]. Although typical conditions in spring (i.e., when a flood for dodder management would be initiated) minimally reduce TNSC, stressed or weakened vines may incur more injury and subsequent yield loss than the weed management strategy prevents.

Cranberry growers currently scout for early emerging seedlings to time herbicide applications[27], and so using early seedling emergence as a biological marker for a flooding event (Fig. 1) would be easy to incorporate into typical scouting activities and an integrated weed management plan. Portions of the farm, such as areas where the fruit are removed during harvest, are likely to have received deposits of dodder seed in the fall and serve as reasonable places to search for seedlings in the spring. Open or thinly vined areas warm quickly in the spring and would be good places to scout for early emerging seedlings. The use of a short-term spring flood is used for other pests and fits well into the typical scope of activities familiar to most growers and would be inexpensive to include in a dodder management program.

Conclusions and Future Research

Results from the initiation/duration experiments showed that short-term floods reduced attachment ratings and dodder stem biomass, with the lowest values obtained with floods initiated at 4 weeks AEE. These results indicate that one must allow time for dodder seed to germinate before applying a short-term flood, suggesting that the short-term floods may impact on emergent dodder seedlings. Delaying the onset of the flooding event until a substantial proportion of the population emerges may offer better management results. Based on that premise, additional areas of research to consider are flooding at various stages of dodder growth (e.g., early germinated seedlings and post-attachment growth stages) that may be more susceptible to flooding (Fig. 1). It may also be useful to explore floods initiated later than 4 weeks AEE to see if a flood initiated later will impact a greater proportion of susceptible growth stages. The impact of dissolved oxygen on dodder germination or growth was not investigated in the present study but should be considered in future research projects. The presence of an additional (herbaceous) host at the time of seed germination as a precursor to successful attachment and its influence on management efforts also warrants further investigation.

Acknowledgements. This work was supported in part by funding from the U.S. Environmental Protection Agency Region 1 Strategic Agricultural Initiative program, Grant X8-97120901. We are also grateful for the additional financial support of this project by the Cape Cod Cranberry Growers' Association. The authors thank K. DeMoranville, N. DeMoranville, J. Moores, T. Revell and D. Shumaker for technical support. Thanks to P. Jeranyama for statistical advice.

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Renewable Agriculture and Food Systems: 26(4); 276–286 doi:10.1017/S1742170511000081

Azinphos-methyl (AZM) phase-out: Actions and attitudes of apple growers in Washington State

Jessica R. Goldberger[1]*, Nadine Lehrer[2], and Jay F. Brunner[3]

[1]Department of Crop and Soil Sciences, Washington State University, Pullman, WA 99164, USA.
[2]Tree Fruit Research and Extension Center, Washington State University, Wenatchee, WA 98801, USA.
[3]Department of Entomology, Tree Fruit Research and Extension Center, Washington State University, Wenatchee, WA 98801, USA.
*Corresponding author: jgoldberger@wsu.edu

Accepted 18 August 2010; First published online 25 February 2011 **Research Paper**

Abstract

The Environmental Protection Agency's phase-out of the pesticide azinphos-methyl (AZM) has encouraged the transition of apple pest management toward more environmentally and socially sustainable practices. This study reports on results of a 2009 survey of conventional apple growers in Washington State. Growers were asked about their approaches and attitudes toward the AZM phase-out and barriers to the adoption of reduced-risk insecticides (AZM-alternatives) as part of their integrated pest management (IPM) programs. Chi-square and analysis of variance (ANOVA) techniques were used to examine relationships between actions and attitudes toward the phase-out and grower characteristics. Results showed that Washington apple growers have begun eliminating AZM and adopting AZM-alternatives. However, larger growers (in terms of acreage and income) and growers more familiar with Washington State University's (WSU's) educational resources were more likely to have already reduced their AZM use. These results suggest that larger farms can play an important role in increasing the sustainability of conventional agriculture, despite a common association of sustainable agriculture with small farms. Results also suggest that agricultural extension services could be well served to extend their outreach to smaller growers and others lagging in the transition to more sustainable apple pest management.

Key words: apple production, azinphos-methyl, integrated pest management, pesticide use, sustainable agriculture, Washington State

Introduction

Pesticide use is an important component of an agricultural system's sustainability. While important for staving off crop loss due to insects and diseases, widespread pesticide use can contaminate water bodies, affect air quality and endanger the health and safety of agricultural workers[1–3]. In Washington State, the apple industry is phasing out its use of the organophosphate (OP) pesticide azinphos-methyl (AZM or Guthion) in compliance with the Environmental Protection Agency's (EPA's) decision to eliminate use of the product after 2012. This policy decision, spurred primarily by environmental groups and worker safety advocates, is likely to improve the environmental and social sustainability of apple (and other AZM-dependent crop) production[4]. AZM has been used in apples since 1959, and is currently applied on the majority of Washington State's apple acres as one of the more effective products available for the control of the key pest codling moth[5,6]. However, it is also a product of concern with regard to human and environmental health[7].

In a state heavily dependent on apple production for its agricultural economy and highly reliant on pesticides to produce quality fruit, the phase-out of one of the Washington apple industry's most used insecticides has presented a challenge to the more than 3000 growers operating over 165,000 acres of apple orchards in the state[8]. While there are OP-alternative insecticides available for managing codling moth that are significantly less toxic for both workers and the environment, they require more precise timing and application techniques, integration with other integrated pest management (IPM) practices such as pheromone mating disruption, monitoring to target specific insect life cycle stages and rotation schemes to prevent insect resistance to new chemicals. The OP-alternatives, as these new chemicals are known, tend to be less effective

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and are more expensive than AZM. Most OP-alternatives are classified by the EPA as reduced-risk products and thus an evolving part of a more environmentally and socially sustainable IPM program in apple production[9].

Because these new IPM-based systems are much more knowledge intensive and complex than previous systems based primarily on OP insecticides, transitioning from AZM to OP-alternatives has presented a challenge to Washington's apple industry. In response to this challenge, Washington State University's Pest Management Transition Project (WSU-PMTP) was started in 2007 with funding from the State Legislature (and continued in 2009 with a USDA Specialty Crop Block Grant) to help growers transition to the use of OP-alternative insecticides and more sustainable IPM programs. Using field- and classroom-based educational sessions, web and print handbooks and newsletters, and regular meetings of small groups of apple growers, pest management consultants and researchers, WSU-PMTP developed a program to help growers eliminate AZM and transition to use of OP-alternatives in apple IPM[9]. Many growers have already begun or completed the transition to a more sustainable apple IPM model even though AZM is still legal for use through 2012.

The transition of a large-scale mainstream agricultural industry toward adoption of new pest control technologies mandated by regulations imposed by the EPA provides the opportunity to ask pointed questions about sustainable agriculture. Sustainability has often, explicitly or implicitly, been associated with small farms[10–12]. Some, however, have questioned this link, arguing that farm and industry size neither facilitates nor precludes the use of sustainable agricultural practices. Born and Purcell[13] argue that farms can easily be sustainable or unsustainable at all scales. Carolan[14] calls attention to the cross-pollination of ideas and practices across sustainable and conventional farms. Warner[15] similarly finds that collaborative learning can play a major role in transitioning conventional farms toward more sustainable practices. Nevertheless, the idea that 'productive' farms are large and 'sustainable' farms are small permeates much of agricultural and public opinion alike. Therefore, this study explores the following question: to what extent can a large mainstream agricultural industry approach or achieve environmental and social sustainability?

This study uses data from a survey of apple growers to assess the transition of Washington State's apple industry away from AZM and toward the adoption of AZM-alternatives and use of IPM practices during the 2008 crop year. It asks what this transition means for sustainability in the apple industry and for the meanings and assumptions embedded in the notion of sustainable agriculture. Specifically, this study focuses on what growers think about the AZM phase-out, the steps they are taking (and not taking) to change their practices and the challenges they face in using AZM-alternatives. Chi-square and analysis of variance (ANOVA) techniques are employed to examine the relationships between actions and attitudes toward the AZM phase-out and orchard and grower characteristics. Known as the 'apple capital' of the USA, Washington State is an appropriate place to investigate these questions and better understand some of the complexities and tensions embedded in the notion and practice of sustainable agriculture, especially in orchard systems.

Methods and Data

Study population and sample selection

The population of interest for this study is all commercial apple growers (except for exclusively organic growers) in Washington State. A random sample of 2000 apple growers was drawn from a list ($N = 3775$) obtained from the Washington Apple Commission. This list included all commercial apple farmers who grow apples as their primary crop and partner with the warehouses handling two-thirds of all Washington apples sales[16]. Small-scale growers may be underrepresented in the sample because of their preferences for direct-to-consumer marketing channels that bypass warehouse channels; however, this population is considered very small relative to the Washington apple industry.

Survey design

The survey questionnaire was developed by WSU-PMTP representatives. The questionnaire consisted of six main sections. The first section focused on the use of OP insecticides, OP-alternatives (e.g., 'softer' insecticides, horticultural oils and mating disruption) and IPM practices (e.g., economic thresholds, degree day models and border sprays) for codling moth control. The second section included similar questions about leafroller control. The third section consisted of questions about the AZM phase-out. Information was collected on awareness of the phase-out, trends in AZM use, knowledge of AZM-alternatives, barriers to using AZM-alternatives and opinions about the phase-out. The fourth section asked about the importance of different sources of information for making pest control decisions. The final two sections focused on orchard characteristics (e.g., acreage, geographic location and gross farm income) and grower demographics (e.g., age, ethnicity and education).

Survey implementation

The survey was conducted with the cooperation of WSU's Social and Economic Sciences Research Center (SESRC). Survey implementation followed the Tailored Design Method (TDM)[17] that centers on a series of carefully designed and timed contacts. The first contact was a cover letter, questionnaire and postage-paid return envelope. A reminder postcard was mailed to everyone approximately a week and a half later. The third contact was sent to non-respondents and included a revised cover letter, replacement questionnaire and postage-paid envelope. A final

Table 1. Attitudinal dependent variables: items included and reliability results.

Items included	Cronbach's alpha
Pro-phase-out	0.848
Phasing out Guthion will have a positive environmental impact	
Phasing out Guthion will protect the health of agricultural workers	
Phasing out Guthion will encourage growers to use safer pesticides	
Phasing out Guthion will provide me with new apple marketing opportunities	
Phasing out Guthion as soon as possible will be beneficial for my operation	
Growers have effective alternatives to Guthion at their disposal	
Anti-phase-out	0.769
Phasing out Guthion will make tree fruit production riskier for growers	
Growers will bear all the burden of the Guthion phase-out	
Growers' opinions were not considered when the EPA decided to phase out Guthion	
The cost of codling moth control will be higher after the Guthion phase-out	
Control of codling moth will be more difficult after the Guthion phase-out	

reminder postcard was sent to non-respondents. A link to an online version of the survey was provided in each mailing. Online surveys were programmed by SESRC staff. Screen layouts followed TDM protocols[17] for maximizing respondent comprehension and ease of navigation. The survey was conducted in February–April 2009.

Five hundred and twenty individuals were excluded from the sample because of ineligibility (e.g., no longer growing apples or growing only organic apples), incorrect contact information or death. The corrected sample totaled 1480 growers. Four hundred and one questionnaires were returned for a response rate of 27%.

Variables

Dependent variables. One action-oriented and two attitudinal dependent variables are included in this study. The first variable, *phase-out action*, is based on the following survey question: 'Which of the following statements best reflects your approach to the Guthion (the common trade name for AZM) phase-out in the apple orchard(s) you own or manage?' Answer categories include: 1 = I have not yet reduced my Guthion use, 2 = I am in the process of reducing my Guthion use, and 3 = I have already stopped using Guthion. Respondents who indicated they had never used Guthion ($N = 5$) or failed to answer the question ($N = 32$) were excluded from the analysis. Of the remaining respondents, 14.1% ($N = 51$) had not yet reduced their Guthion use, 67.1% ($N = 243$) were in the process of reducing their Guthion use and 18.8% ($N = 68$) had already stopped using Guthion. The two attitudinal dependent variables are summated scales composed of responses to Likert items with five ordered response levels: 1 = strongly disagree, 2 = disagree, 3 = neither disagree nor agree, 4 = agree, and 5 = strongly agree. *Pro-phase-out* measures positive attitudes toward the AZM phase-out and ranges from 6 to 30 (mean of 17.6). *Anti-phase-out* measures negative attitudes and ranges from 7 to 25 (mean of 19.7). The high Cronbach's alpha coefficients confirm the internal reliability of the two scales. Table 1 presents the items included in each scale and reliability results.

Independent variables. The independent variable groups include grower demographics, farm size variables, variables measuring codling moth damage and variables measuring experience with Washington State University. All the independent variables presented in the tables were measured by direct survey questions. The continuous variables (e.g., total apple acres) were recoded as categorical variables for the purpose of analysis.

After a series of closed-ended questions about the AZM phase-out, survey respondents were also asked to share their thoughts about the phase-out. Selected responses to this open-ended question are presented to complement the quantitative data.

Statistical analysis. Survey data were analyzed using the statistical package SPSS. Frequency distributions, cross tabulations, Pearson chi-square tests and one-way ANOVA were used to explore the relationships between the dependent and independent variables. The Pearson chi-square test is designed to test for independence between two nominal variables. The null hypothesis is that the two variables are statistically independent. The test is based on a comparison between the observed and expected frequencies in cross-tabulation cells. ANOVA is a statistical test designed to measure whether the means of two or more groups are equal.

Results

AZM phase-out actions and attitudes

Table 2 presents percentage distributions for AZM phase-out action by two grower demographic variables: age and education. There is a statistically significant difference in AZM phase-out action for age, but not education. Older growers are more likely than younger growers to have not yet reduced their AZM use. Growers aged 45–54 are most likely to have already stopped using AZM.

Table 2. Percentage distribution of AZM phase-out action by grower demographics, Washington apple growers, 2008.

Grower demographics	WA apple growers (%)			χ^2	*P*-value
	Not yet reduced AZM use	In process of reducing AZM use	Already stopped AZM use		
Age					
Under 45	8.0	74.0	18.0		
45–54	9.8	61.5	28.7		
55–64	11.1	72.2	16.7		
65 and over	25.3	66.7	8.0	23.135	0.001
Education					
High-school degree or less	17.5	73.0	9.5		
Some college	15.5	66.7	17.9		
Vocational degree	8.3	83.3	8.3		
College degree	12.9	63.2	12.9		
Some postgraduate work	4.5	77.3	18.2		
Postgraduate degree	18.2	59.1	22.7	10.323	0.413

Table 3. Percentage distribution of AZM phase-out action by farm size variables, Washington apple growers, 2008.

Farm characteristics	WA apple growers (%)			χ^2	*P*-value
	Not yet reduced AZM use	In process of reducing AZM use	Already stopped AZM use		
Acres of apples (2008)					
1.0–9.9 acres	25.0	57.4	17.6		
10.0–24.9 acres	15.5	77.5	7.0		
25.0–49.9 acres	15.8	66.7	17.5		
50.0–99.9 acres	6.7	68.9	24.4		
100.0–249.9 acres	1.9	57.7	40.4		
250.0 acres or more	5.6	79.6	14.8	40.047	0.000
Gross income from apples (2008)					
Less than $25,000	28.8	61.5	9.6		
$25,000–$49,999	17.5	70.0	12.5		
$50,000–$99,999	12.9	64.5	22.6		
$100,000–$249,999	17.4	69.6	13.0		
$250,000–$499,999	9.5	73.8	16.7		
$500,000–$999,999	2.7	59.5	37.8		
$1 million–$2.4 million	0.0	65.5	34.5		
$2.5 million–$5 million	0.0	88.9	11.1		
$5 million or more	11.1	50.0	38.9	42.762	0.000

Table 3 presents percentage distributions for AZM phase-out action by two farm size variables: apple acreage and gross income from apples. Chi-square results indicate statistically significant relationships between AZM phase-out action and both farm size variables. Small-scale growers (under 50 acres) are more likely to have not yet reduced their AZM use compared to larger-scale growers (50 acres or more). Only 7% of growers with 10–24 acres have stopped using AZM compared to over 40% of growers with 100–249 acres. Similarly, growers with less than $250,000 gross apple income are more likely to have not yet reduced their AZM use compared to larger-income growers ($250,000 or more). Approximately 10% of growers with less than $25,000 gross apple income have stopped using AZM compared to nearly 39% of growers with gross apple income of $5 million or more.

Table 4 presents percentage distributions for AZM phase-out action by two variables that measure experience with codling moth damage. Survey respondents were asked if codling moths had caused unacceptable crop damage in their apple orchards during 2006–2008. They were also asked about the frequency of unacceptable crop damage caused by codling moths. The Chi-square results reported in Table 4 indicate no statistically significant relationship between AZM phase-out action and experience with codling moth damage.

Table 5 presents percentage distributions for AZM phase-out action by three variables that measure experience

Table 4. Percentage distribution of AZM phase-out action by codling moth damage variables, Washington apple growers, 2008.

	WA apple growers (%)				
Codling moth damage	**Not yet reduced AZM use**	**In process of reducing AZM use**	**Already stopped AZM use**	χ^2	***P*-value**
Unacceptable codling moth damage (2006–2008)					
No	14.6	65.8	19.6		
Yes	13.7	68.1	18.1	0.219	0.896
Frequency of unacceptable codling moth damage					
Never	16.1	58.6	25.3		
Less than every year	12.4	68.9	18.7		
Every year	18.2	70.9	10.9	6.133	0.189

Table 5. Percentage distribution of AZM phase-out action by variables measuring experience with WSU, Washington apple growers, 2008.

	WA apple growers (%)				
Experience with WSU	**Not yet reduced AZM use**	**In process of reducing AZM use**	**Already stopped AZM use**	χ^2	***P*-value**
Used WSU Decision Aid System to guide pest management practices in 2008					
No	18.4	67.6	14.0		
Yes	6.6	64.8	28.7	16.242	0.000
Aware of WSU Pest Management Transition Project					
No	17.6	72.7	9.7		
Yes	8.5	63.8	27.7	21.407	0.000
Participated in WSU Pest Management Transition Project Implementation Unit in 2008					
No	14.8	70.1	15.1		
Yes	3.2	58.1	38.7	21.203	0.000

with Washington State University. AZM phase-out action appears to be significantly influenced by growers' use of the Washington State University Decision Aid System (WSU-DAS, a web-based tool that integrates phenology models for insects and diseases with management recommendations), awareness of the WSU-PMTP and participation in WSU-PMTP Implementation Units (groups of growers and orchard managers who farm in close proximity and want to learn about OP-alternatives and IPM practices). Growers who reported awareness of and participation in WSU's programs are more likely to have already stopped using AZM. Nearly 29% of WSU-DAS users have stopped using AZM compared to 14% of non-users. Similarly, nearly 39% of Implementation Unit participants have stopped using AZM compared to 15% of non-participants.

Table 6 presents one-way ANOVA results for the two attitudinal dependent variables (pro-phase-out and anti-phase-out) and nine independent variables. Attitudes about the AZM phase-out appear to be influenced by awareness of and participation in WSU's programs. Respondents familiar with the WSU-DAS and WSU-PMTP are more likely to agree that the AZM phase-out will have positive environmental, health and marketing impacts. In addition, these respondents are less likely to agree that the phase-out will increase production risks and pest management costs. Table 6 also includes ANOVA results for the two attitudinal variables and phase-out action. Respondents who have already stopped using AZM score significantly higher on the pro-phase-out scale and lower on the anti-phase-out scale compared to respondents who have not yet reduced their AZM use.

Table 7 presents growers' responses to the open-ended survey question about the AZM phase-out. Responses were grouped into either 'positive' or 'negative' categories. Table 7 includes the categories, number of comments per category and sample comments (full comments are available from the authors). Forty 'positive' comments included general pro-phase-out opinions, testimonies of successful phase-out experiences, praise for WSU research on alternatives and concern about AZM's reduced effectiveness. Ninety-two 'negative' comments included general anti-phase-out opinions, support for AZM's safety and effectiveness, recommendations for preserving AZM use for specific circumstances, concerns about AZM-alternatives' cost and effectiveness, and feelings that the phase-out is more about politics than facts.

Table 6. ANOVA of attitudinal-dependent variables by independent variables, Washington apple growers, 2008.

Independent variables	d.f.	Pro-phase-out		Anti-phase-out	
		F	*P*-value	*F*	*P*-value
Age	3	1.401	0.242	1.592	0.191
Education	5	0.744	0.591	0.693	0.629
Acres of apples (2008)	5	0.443	0.818	0.370	0.869
Gross income from apples (2008)	8	1.396	0.197	1.041	0.405
Unacceptable codling moth damage (2006–2008)	1	3.302	0.070	0.111	0.739
Frequency of unacceptable codling moth damage	2	2.490	0.084	2.887	0.057
Used WSU Decision Aid System to guide pest management practices in 2008	1	4.173	0.042	6.559	0.011
Aware of WSU Pest Management Transition Project	1	9.962	0.002	11.271	0.001
Participated in WSU Pest Management Transition Project Implementation Unit in 2008	1	17.953	0.000	21.845	0.000
Phase-out action	2	39.947	0.000	47.325	0.000

Table 7. Washington apple growers' responses to open-ended question about AZM phase-out.

Category	Number of comments	Sample comments
Pro phase-out	24	• Guthion is no longer the silver bullet—time has run its course. • Whether we as growers approve or disapprove, Guthion is gone. We have more than enough tools to deal with apple pest problems. Are we as growers willing to step up and do what needs to take place? I am willing.
AZM no longer effective	9	• Guthion by itself was not as effective as it had been—more treatments were required. We had better control last year with a variety of OP-alternatives than we had with Guthion. • The effectiveness of Guthion continually decreases so what choice do we as growers have?
WSU resources	4	• WSU has a very strong research program to get growers ready for phase-out.
No longer using AZM	3	• We have already stopped using Guthion. Codling moth control is equal or better than when we used Guthion. It is safer and easier to manage our crew schedules without the use of Guthion. • We have used pheromones and alternatives to Guthion for several years.
Total 'positive' comments	40	
Anti phase-out	17	• I think it is moving in the wrong direction to phase out Guthion.
AZM is safe	12	• I believe that the dangers of OPs have been exaggerated. Ninety-nine percent of all growers have always protected their employees and consumers.
AZM is effective	6	• Guthion is a safe and effective product. Codling moth resistance and food safety issues regarding the proper use of Guthion is perception driven much more than factual.
Keep AZM for limited use	11	• Guthion should be left as a remedy for future outbreaks. It can be used as an emergency use chemical by recommendation by my fieldmen. • I am confident that cautious and judicious use of Guthion is the best option we have.
Alternatives are not effective	7	• I do not believe we are ready for replacing Guthion yet. I am not against a replacement, but I have not seen great results from any replacements yet.
Alternatives are expensive	21	• It will become even more expensive for the grower to control codling moth. • We will probably manage to survive with these new tools, but it will hit hard on our pockets.
Phase-out is political	18	• This phase-out is the result of environmentalists' pressure on our government. • The people who are pushing for this phase-out do not care if farmers survive. They only care about their 'green' agenda.
Total 'negative' comments	92	

Perceived barriers and changing practices

This study not only focuses on the determinants of AZM phase-out actions and attitudes (as described above) but also seeks to understand the perceived barriers to using AZM-alternatives as well as trends in apple growers' use of OPs, OP-alternatives and IPM practices. Table 8 presents the percentage of growers facing each of the listed barriers to using AZM-alternatives. Nearly 68% of growers believe AZM-alternatives are too expensive; 53% believe they are

Table 8. Barriers faced by Washington apple growers to using AZM-alternatives.

Barriers	Growers (%)
Alternatives are too expensive	67.8
Alternatives are not as effective	52.9
Alternatives cause other pest problems	42.5
Export markets might not accept fruit with alternative insecticide residues	29.2
The timing of alternatives is confusing	26.3
There are too many alternatives to choose from	12.3
Other barriers	7.4
No barriers faced in using alternatives	14.1

not as effective as AZM; and 43% believe they cause other pest problems. Fourteen percent of growers reported they do not face barriers to using AZM-alternatives.

Perceptions of barriers to using AZM-alternatives are influenced by grower demographics, farm size variables, variables measuring codling moth damage and variables measuring experience with WSU. Chi-square results (available from the authors) indicate statistically significant relationships between each of the items listed in Table 8 and from one to seven of the independent variables. For example, respondents who are 65 years or older, respondents who experienced unacceptable codling moth damage in 2006–2008, and WSU-DAS users are more likely to perceive the expense of AZM-alternatives as an adoption barrier. Respondents who experienced unacceptable codling moth damage and those unfamiliar with the WSU-PMTP are more likely to perceive the effectiveness of AZM-alternatives as an adoption barrier.

Perceived barriers are also correlated with phase-out action and attitudes. Chi-square results (available from the authors) indicate statistically significant relationships between phase-out action and three of the perceived barriers to using AZM-alternatives: effectiveness of alternatives, too many alternatives and confusing timing of alternatives. In addition, growers who have already stopped using AZM are more likely than growers who have not yet reduced their AZM use to report no barriers to using AZM-alternatives (28% compared to 4%). Finally, *t*-test results (available from the authors) indicate that respondents who face five of the barriers listed in Table 8 score higher on the anti-phase-out attitudinal scale. Moreover, respondents who do not face any barriers in using AZM-alternatives are more likely than other respondents to have positive attitudes about the AZM phase-out.

Table 9 presents Washington apple growers' use of OP insecticides, OP-alternatives and IPM practices for codling moth control between 2006 and 2008. During this time period, 50% of respondents decreased their use of OP insecticides and 46% increased their use of OP-alternatives. An overwhelming majority of respondents maintained or increased their use of IPM practices. At least one-quarter of respondents increased their use of pheromone traps, degree day models, field monitoring for damage and resistance management strategies between 2006 and 2008.

Discussion

This study revealed several interesting relationships between growers' AZM phase-out actions and attitudes and various independent variables, particularly grower age, scale of operation, codling moth damage, experience with university educational outreach programs and barriers to adoption of OP-alternatives.

Grower age and phase-out action

Apple growers aged 45–54 are more likely than younger and older growers to have already stopped using AZM (Table 2). This finding is not surprising given that growers in this age group tend to have larger-scale operations and are the most likely to use the WSU-DAS, know about the WSU-PMTP, and participate in WSU-PMTP Implementation Units. In addition, they are the most likely to have decreased their use of OP insecticides (in general) for codling moth control between 2006 and 2008. Whether seeking out WSU resources and programs on their own or 'targeted' by WSU (and other entities) as potential early adopters of OP-alternatives, growers aged 45–54 appear to be the vanguard in the transition to more environmentally and socially sustainable IPM programs. Moreover, unlike beginning apple growers or those close to retirement, growers aged 45–54 are likely to have developed the clout, resources and frame of mind to innovate.

Grower size and phase-out action

Instructive for questions of sustainability is the finding that small-scale growers (under 50 acres) and those with lower gross apple incomes (under $250,000) were more likely to have not yet reduced AZM use compared to larger-scale and larger-income growers (Table 3). This supports what Born and Purcell[13] suggested, that small does not necessarily mean more environmentally or socially sustainable, at least in terms of orchard pest management. While philosophically motivated small-scale organic or alternative farmers—many of whom were omitted from this survey because they only grew organic fruit or sold through direct-marketing channels—might be more likely to embrace sustainable pest management, smaller-scale conventional growers were less likely than larger growers to quickly phase out AZM.

There are many likely reasons for this finding. First, the higher costs of alternative pest control technologies can be intimidating (Table 8). Perhaps these costs are prohibitive for growers who do not experience the economies of scale (or bulk pesticide purchasing discounts) that larger growers do. However, analysis of the survey data indicated that smaller orchardists (in terms of apple acreage and gross income) were no more likely than larger orchardists to perceive the expense of AZM-alternatives as an adoption

Table 9. Washington apple growers' use of different pest management approaches for codling moth control, 2006–2008.

Pest management approach	2006–2008 usage (% growers)			
	Use decreased	Use remained the same	Use increased	Did not use
Organophosphate (OP) insecticides[1]	49.9	39.3	6.2	4.7
OP-alternatives[2]	12.6	36.6	46.1	4.7
Integrated pest management (IPM)				
Resistance management strategies	2.3	45.0	31.3	21.4
Field monitoring for damage	4.7	65.9	26.5	2.9
Degree day models	3.0	58.6	26.5	11.9
Pheromone traps	3.5	59.9	24.8	11.7
Border sprays	4.9	51.4	19.7	24.0
Delayed distribution of bins	1.4	63.9	16.8	17.9
Economic or treatment thresholds	3.2	56.8	13.6	26.4
Reduced pesticide rates	8.8	45.9	8.3	37.0
Biological controls	3.2	38.1	6.0	52.7
Alternate row spraying	7.2	42.9	5.3	44.6

[1] OP insecticides included Guthion, Diazinon and Imidan.
[2] OP-alternatives included Assail, Calypso, Esteem, Altacor, Delegate, Rimon, Intrepid, Entrust/Success, pheromone mating disruption, horticultural spray oil and CM granulosis virus.

barrier. Moreover, the 21 respondents whose open-ended comments mentioned the high cost of AZM-alternatives (see Table 7) included equal numbers of small-, medium- and large-scale growers.

Second, larger tree fruit companies, who frequently pack and sell their fruit under their company brand, are often more visible to the public than small-scale conventional growers who send fruit to an unaffiliated warehouse to be marketed jointly with other fruit under a separate brand name. As such, larger growers who pack their own fruit are more susceptible to current and increasing public pressure for sustainability in food production, and are thus also more able to benefit from marketing and selling their fruit as 'sustainably grown' (see Florax et al.[18] for consumer willingness to pay for such products).

Third, many larger tree fruit companies have entered the market for organic apples, while maintaining production of their conventionally produced fruit. Survey results indicate a statistically significant relationship between total apple orchard acreage and production of certified organic apples. Less than 3% of the smaller-scale growers (<50 apple acres) compared to 44% of the largest growers (250 apple acres or more) operated some certified organic apple acres. Consequently, larger growers may be more familiar than smaller-scale growers with the pest management practices and principles that cross-pollinate between organic and conventional systems, as suggested by Carolan[14]. In other words, larger growers with both conventional and organic apple acres may be more aware of alternative markets and production practices and, thus, more willing to innovate.

Finally, different levels of access to information about the AZM phase-out may result in different phase-out actions. Survey results suggest a statistically significant relationship between orchard size (measured in terms of acres and gross apple income) and familiarity with WSU educational outreach activities for learning about the AZM phase-out and alternative technologies. Larger growers are more likely than small-scale growers to use the WSU Decision Aid System, know about the WSU-PMTP, and participate in WSU-PMTP Implementation Units. Greater familiarity among larger growers with these WSU services may reflect broader shifts in agricultural extension from on-farm visits (regardless of operation size) to less individual-based forms of information dissemination, such as online resources and group workshops. The latter may favor larger growers who have the manpower and financial resources to take advantage of multiple types of information dissemination strategies.

Similarly, larger growers may have greater access to the services of non-university-based pest management consultants. Their larger acreages may make them a higher priority for visits from agricultural chemical distributor fieldmen and warehouse consultants. Moreover, larger growers may have the resources to employ their own in-house pest management consultants who can focus specifically on pest management decisions in their orchards.

Codling moth damage and phase-out action

Because AZM is the product with the greatest effectiveness per unit cost for controlling codling moth, one might think that growers with greater codling moth damage would be slower to phase out AZM. However, survey results showed no significant relationship between perceived extent of crop damage and AZM phase-out action (Table 4) or attitudes (Table 6). One explanation for these results is the apple industry's zero or very low tolerance for codling moth in apples, specifically for apples designated for export. In 2002, Taiwan ruled that the discovery of three codling moths in US apple shipments in any given crop year would

result in the closing of the Taiwanese market to all US apple imports[19]. Since then, warehouses and shippers have been very careful in inspecting and rejecting damaged fruit from growers, and growers have been vigilant in spraying for codling moth as needed. In other words, the apparent non-relationship between codling moth damage and AZM phase-out action (and attitudes) is likely due to the very minimal amount of fruit damage found across the Washington State apple industry overall[20].

Experience with WSU and phase-out action and attitudes

Another robust finding is the significant relationship between growers' AZM phase-out actions and attitudes and their experiences with WSU educational outreach programs. As discussed above, the WSU-PMTP seeks to assist growers in the transition from AZM to more sustainable OP-alternatives and IPM practices. The WSU Decision Aid System and WSU-PMTP Implementation Units are cornerstones of this program. Chi-square and ANOVA analyses (Tables 5 and 6) suggest that WSU programs are successfully contributing to changing practices and attitudes with regard to the phase-out of the apple industry's most relied-upon insecticide, AZM. This impact is especially visible among larger-scale apple growers who are more likely than small-scale apple growers to use the WSU-DAS, know about the WSU-PMTP, and participate in WSU-PMTP Implementation Units (as discussed above). These findings, however, do not necessarily mean that WSU educational outreach programs have had a *direct* impact on growers' pest management practices. Alternatively, these findings could indicate that growers who are more inclined to adopt new practices are also more inclined to seek out new information.

Barriers to the adoption of AZM-alternatives and IPM

This study found that the greatest barriers to the adoption of AZM-alternatives were cost, concern over product effectiveness and creation of new pest problems (Table 8). Older growers (65 years or older) were more likely than younger growers to perceive cost as a barrier, perhaps because of their attachment to times when codling moth control options were cheaper. Similarly, growers who experienced unacceptable codling moth damage in 2006–2008—and who thus probably relied more on AZM and faced increased costs upon switching to alternative insecticides—were more likely than other growers to perceive the expense of AZM-alternatives as an adoption barrier. Lastly, WSU-DAS users, who may have a more thorough and sophisticated knowledge of pest management options and their relative price tags, also saw cost as a barrier.

While helpful for understanding grower perspectives and willingness to innovate, cost is determined by the companies producing each insecticide. In contrast, the other perceived barriers to adoption of AZM alternatives (namely, secondary pest problems and the effectiveness of AZM-alternatives) can be more easily addressed through research and extension efforts. Research is under way to understand and minimize the impacts of AZM-alternatives on secondary pest outbreaks[21]. The effectiveness of AZM-alternatives is a concern addressed through education and outreach programs such as the WSU-PMTP. Accordingly, growers familiar with the WSU-PMTP (i.e., those exposed to research and outreach on AZM-alternatives) did not see AZM-alternatives' effectiveness as an adoption barrier. Similarly, growers who had stopped using AZM did not feel that alternatives were less effective, that there were too many alternatives or that the timing of alternatives was confusing. In other words, there is a learning curve associated with the effective incorporation of AZM-alternatives into IPM programs, as a product's effectiveness depends on a strong understanding of insect life cycles and how best to target use of different chemistries.

These findings make a case for educational programs that help growers more effectively incorporate OP-alternatives into IPM programs. They also provide feedback to help strengthen such educational programs. By knowing which adoption barriers are associated with particular grower characteristics (age, codling moth damage and familiarity with WSU resources), educators can better tailor training to meet growers' needs. For example, extending outreach to target smaller (in addition to the larger) conventional growers could help the Washington apple industry become more fully sustainable in its pest management practices.

Finally, despite these barriers to adopting AZM-alternatives and IPM practices, and despite the many growers who have not yet phased out AZM, this study shows that the Washington apple industry is in large part moving toward softer and more sustainable IPM systems (Table 9). Half of the growers surveyed decreased their OP use between 2006 and 2008, and almost half increased their use of OP-alternatives, including high levels of pheromone mating disruption. Much of this change is likely due to AZM regulation, which has necessitated a switch to alternative methods of pest control. The move to increasingly sustainable pest management is thus not necessarily the philosophically driven adoption associated with sustainable agriculture that permeates public discussions of sustainability (see Table 7, for example, for negative attitudes expressed toward the phase-out). Nevertheless, it does represent an important and meaningful change in sustainability practices being adopted by Washington's apple industry, one spearheaded in this case by large-scale, conventional orchards.

Conclusion

Sustainable agriculture has been regarded by some as a philosophy by which farmers make a living through a more harmonious relationship with other beings and the environment. Others have viewed it more instrumentally as a specific set of agricultural practices that protect soil, water,

air quality and human health[22]. For those working in the area of sustainability and food systems, it becomes important to consider these different definitions of sustainable agriculture and how they appeal (or do not appeal) to specific groups and individuals in order to target research, outreach and policy activities to appropriate audiences and goals.

In this study, Washington apple growers transitioning from an OP-based management system for codling moth to an OP-alternative and more biologically intensive IPM system were pushed in this direction by regulatory change. Interestingly, those transitioning fastest were owners of larger orchards (both in terms of size and income), growers in lower-to-middle-age ranges (45–54), and those who had interacted with WSU educational outreach programs. However, they were neither necessarily the ones most philosophically committed to the idea of sustainability nor were they the smaller-scale growers most often associated with sustainable agriculture movements. Nevertheless, as they transition their orchards toward increasingly sustainable practices in pest management, the impacts made on these larger acreages to soil, water, air quality and human health are substantive, at least according to the more instrumental (rather than strictly philosophical) definitions of sustainable agriculture.

This study thus encourages a broader look at sustainability, especially with regard to promoting sustainable agriculture across materially and philosophically different types of farms and farm operators. As Warner[15] suggests, while some farmers may be philosophically committed to sustainable agriculture principles, others can contribute equally to a more environmentally, economically and socially sustainable agricultural sector if provided incentives or regulatory structures that uphold a strong commitment to a robustly sustainable agriculture (though see Guthman[23] on the 'watering down' of organic production principles through similar mechanisms). Sustainable agriculture advocates should be mindful of the multiple perspectives of actors differentially embedded in 'sustainable' agricultural operations and the possibilities for and implications of working toward such sustainability on its many possible levels.

Acknowledgements. We thank Jim McFerson (Manager, Washington Tree Fruit Research Commission) for his input during this project, and Todd Fryhover and Don Zones at the Washington Apple Commission for graciously providing a list of Washington apple growers. We also wish to acknowledge Rose Krebill-Prather and Leona Ding at WSU's Social and Economic Sciences Research Center for their assistance with survey implementation, web programming and data management. This work was funded by the Washington State Legislature, a USDA/WSDA Specialty Crop Block Grant (No. K273) and the William D. Ruckelshaus Center's Agricultural Pilots Program.

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Renewable Agriculture and Food Systems: 26(4); 287–296 doi:10.1017/S1742170511000093

Combining current land use and farmers' knowledge to design land-use requirements and improve land suitability evaluation

Feras M. Ziadat[1,2] and Kais A. Sultan[3,*]

[1]International Center for Agricultural Research in the Dry Areas (ICARDA), P.O. Box 5466, Aleppo, Syria.
[2]Department of Land, Water and Environment, Faculty of Agriculture, University of Jordan, P.O. Box 13693, Amman 11942, Jordan.
[3]General Commission for Scientific Agricultural Research (GCSAR), P.O. Box 13348 Damascus, Syria.
*Corresponding author: kaissultan@hotmail.com

Accepted 26 January 2011; First published online 14 March 2011 **Research Paper**

Abstract

Land suitability analysis is very important to assess and propose the most suitable land-use options. The reliability of land suitability evaluation is controlled by choosing the most limiting land characteristics and their ratings for the proposed land utilization types (LUTs). This study aims at examining the possibility of using current land use and farmers' knowledge as a starting point to suggest and/or modify land evaluation criteria, and to improve the land suitability evaluation process. The potential suitability of land for five LUTs (open range, improved range, rainfed barley, drip-irrigated vegetables and drip-irrigated trees) was evaluated near Al-Mafraq in Jordan using the maximum limitation method. The results indicated variable agreement levels between potential land suitability and current land use for different LUTs. Sixteen farms were selected to represent different cases of disagreement between potential suitability and current land use and were visited to explore the farmers' improved management practices adopted to overcome land-use limitations. Using proposed criteria, only 1% of the study area was highly suitable for drip irrigation, whereas most of the area was moderately or marginally suitable for other uses. This represents the conventional land evaluation procedures, which, in most cases, overlook the farmers' knowledge and practices that are adopted in a particular area to overcome biophysical limitations. The ratings for different land characteristics were modified based on comparisons with current land use, and by referring to farmers' adopted management practices. Using modified criteria, the highly suitable area for drip-irrigated vegetables increased by 18% and the highly suitable area for drip-irrigated trees increased by 25%. The results emphasized that the consideration of the farmer's indigenous knowledge and current land use improve the land evaluation process, which leads to better utilization of limited land resources in fragile environments.

Key words: soil survey, sustainable land use, indigenous knowledge, GIS, remote sensing, Jordan

Introduction

Land resources are limited, and therefore, there is an urgent need to optimize land use in the most practicable and logical way to continue sustainable production while conserving fragile ecosystems[1,2]. Jordan is generally dominated by an arid to semi-arid climate and characterized by dry, hot summers and mild, wet winters with extreme variability in rainfall[3]. Limited natural resources in combination with a growing population[4] necessitate the improvement of agricultural productivity. To achieve this, appropriate and sustainable land-use schemes are required. The first step in their development is the evaluation of the biophysical land resources. Crop-land suitability analysis is a prerequisite to achieving sustainable utilization of available land resources and mitigating land degradation[5,6].

The FAO framework[7] is an approach for land suitability evaluation, which classifies land in terms of suitability ratings from highly suitable to not suitable based on soil, climate and terrain properties[6,8]. The approach starts by identifying relevant land-use types, which includes levels of know-how, available technology and available inputs and also the land tenure situation, to indicate the degree to which the land user can manage or overcome constraining land qualities. However, in most cases, land evaluation includes little information about adopted farmers' practices

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that are specific to the area under consideration, which results in a mismatch between land suitability and current land use.

Many factors determine the accuracy of the results from such land suitability evaluation. Among these are the selection of land characteristics that are most limiting for the specified land uses, as well as the ratings given to each of the land characteristics. In most cases, the limiting land characteristics are chosen and their ratings are defined based on results from other similar areas or using expert knowledge. Hence, there is the uncertainty of the limiting land characteristics chosen and the uncertainty of their ratings. Adaptation of land-use requirements to local varieties, management techniques and environmental conditions is often neglected, resulting in land suitability classifications of low reliability. This raises questions about the reliability of the final suitability map and its use in land-use planning[9].

Land suitability evaluation is widely used by many projects and researches[3,10–14]. However, the results of land evaluation are used as inputs for land-use planning exercises without comparing these results with the current land-use pattern, and without taking the farmer's knowledge into consideration. Comparison of the current land-use map, which also reflects the farmer's indigenous knowledge, with the suitability maps is useful to identify differences or similarities between the present land use and the potential suitability of an area for proposed land utilization types (LUTs)[15,16]. This is simply because farmers have farmed their region long enough to know which sites are suited for particular uses and how to adapt to limitations imposed by the prevailing ecosystem[17,18].

Farmers and land resource professionals assess the options that optimize the productivity and sustainability through different knowledge systems. Both systems have advantages and drawbacks[19,20]. The use of conventional soil survey information in traditional rural societies frequently fails because it does not take into account soil knowledge and experience of local people[21]. Merging technical and local thinking is indispensable to formulate sustainable land management schemes[18,22,23]. Agricultural land suitability classification based on indigenous knowledge is vital to select and put into practice sustainable land uses[1,24–27].

Adaptation of land use to the potentials and constraints of the agro-ecosystem is a key principle of sustainable land management[2,19]. Therefore, it is not only the biophysical factors (e.g., soil, climate or parcels of land) that are important, information representing the people involved in the planning process is also of critical importance[28–30]. Therefore, it is important to verify the land suitability evaluation results, for which the consideration of current land use and farmers' knowledge are of great value[17].

The objectives of this study were to compare the current land use with land suitability, and to modify the land suitability evaluation process according to field verifications and farmers' adopted technologies and knowledge.

Figure 1. Location of Al-Mafraq study area within Jordan.

Methodology

Study area

The study area is located in the north of Jordan between the latitudes 32°22′ and 32°45′ north and longitudes 36°22′ and 36°45′ east, and covers an area of 148 km^2 (Fig. 1). Most of the area is formed from old colluvial material dominated by Calcids with inclusions of Cambids soils[31]. Generally, it is a very gently undulating lava plain with dominant slopes between 1 and 4% at an altitude of 650–750 m above sea level. Most of the soils have a transitional xeric–aridic moisture regime and thermic temperature regime[31]. The mean annual precipitation is 175 mm. The average annual temperature is 16.5°C, the mean daily minimum temperature is 9.2°C and the maximum temperature is 23.9°C. The mean relative humidity is 56%[32].

Land suitability evaluation

The land suitability was evaluated based on the FAO framework for land evaluation[7]. LUTs were selected taking into account previous research in the study area in particular and in Jordan in general[3,10,11,14,16]. An important assumption was that the low rainfall in the study area could not sustain rain-fed agriculture[3,10]. However, rain-fed agriculture is still practiced in the study area, because farmers expect 1 out of 3 years to have some rainfall for marginal production. The general prevailing land-use pattern in the study area was also considered in the selection process. The following LUTs were selected: open range, improved range by using small pits for water harvesting; rain-fed barley for livestock grazing; drip-irrigated vegetables; and drip-irrigated trees.

Land qualities were selected and the rating of criteria for land suitability classification were derived and modified

Table 1. Land-use limitations, land qualities and land characteristics.

Limitation	Land qualities	Land characteristic	Unit
Climate	Moisture regime	Average annual precipitation	mm
	Temperature regime	WGPT[1]	Degree-days
Soil	Rooting condition	Available water-holding capacity	mm/m
		Soil depth	cm
Erosion	Erosion	Rill or gully erosion	Class
		Sheet/wind/undifferentiated	Class
Topography	Topography	Slope	%
Rock outcrop/stones	Conditions for germination	Rock outcrop	%
		Stone at surface	%
		Stone content in surface horizon	%

[1] WGPT: summation of degrees greater than 8°C during the coldest months (December, January and February).

Table 2. Land-use requirements for different LUTs.

Land	Open range				Improved range				Rain-fed barley				Irrigated vegetables				Irrigated trees			
characteristic	S1[1]	S2	S3	NS	S1	S2	S3	NS	S1	S2	S3	NS	S1	S2	S3	NS	S1	S2	S3	NS
Precipitation	100	75	50	<50	200	150	100	<100	250	200	150	<150	NL[2]	NL	NL	NL	NL	NL	NL	NL
WGPT[3]	400	250	NL	NL	400	250	NL	NL	>250	NL	NL	NL	400	250	<250	–	>250	NL	NL	NL
AWHC[4]	90	60	30	<30	110	75	50	<50	150	110	75	<75	110	75	50	<50	110	75	50	<50
Soil depth	50	35	10	<10	100	70	40	<40	90	60	30	<30	100	50	25	<25	150	100	50	<50
Rill or Gully[5]	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Sheet/Wind/ Undiff[5]	1,2	3	4	–	1,2	3	4	–	1,2	3	4	–	1,2	3	4	–	1,2	3	4	–
Slope	<20	<40	<80	>80	<8	<12	<20	>20	<5	<8	<16	>16	<5	<8	<16	>16	<5	<8	<16	>16
Rock outcrop	<20	<50	>50	–	<10	<20	<35	>35	<6	<10	<20	>20	<3	<5	<10	>10	<3	<5	<10	>10
Stone at surface	<30	<60	>60	–	<20	<40	<60	>60	<20	<40	<60	>60	<6	<10	<20	>20	<6	<10	<20	>20
Stone content[6]	<20	<50	>50	–	<10	<20	<35	>35	<10	<20	<30	>30	<6	<10	<20	>20	<6	<10	<20	>20

Source: MoA[10], Mazahreh[11] and Hatten and Taimeh[3].
[1] Suitability classes: S1, highly suitable; S2, moderately suitable; S3, marginally suitable; NS, not suitable.
[2] NL, not limiting.
[3] WGPT, winter growth potential (summation of degrees >8°C during the coldest months).
[4] AWHC, available water-holding capacity.
[5] Erosion class: 1 = nil, 2 = slight, 3 = moderate, 4 = severe.
[6] Stone content in the surface horizon.

based on previous research[3,10,11,13,16]. A major consideration in the selection of land qualities is their expected effect on the use and management of land for the selected LUTs. The National Soil Map and Land Use Project (NSMLUP)[10] and Jordan Arid Zone Productivity Project (JAZPP)[3] aggregated the required land qualities and their characteristics into five main groupings: Climate, Soil, Erosion, Topography and Rock outcrop/stones. Table 1 summarizes the selected land-use limitations, the land qualities and land characteristics used to account for the effect of each limitation. Table 2 shows the land-use requirements in terms of land qualities and land characteristics for each of the selected land-use types. These are the requirements that are usually considered by conventional land suitability analyses, i.e., without thorough considerations of farmers' adopted practices that are specific to a particular area. In this research, land suitability was done using these 'original' land-use requirements and were then adjusted according to farmers' adopted practices.

The main source of information for this land suitability analysis was derived from NSMLUP[10]. The data exist as original paper maps (scale 1 : 10,000), tables and digitized information entered into the Jordan Soil and Climate Information System (JOSCIS) database. The relevant data in this database are the 2193 soil observations (pits and auger holes) collected during the soil survey. The land-use requirements (Table 2) determine the required factors for land suitability analysis. These factors are: rainfall, temperature, soil depth, available water-holding capacity, slope, surface stoniness, erosion type and class, surface cover type (stones, boulders, rock outcrop) and percentage of surface cover.

The evaluation procedure was based on the simple limitation system. This implies that suitability classes, namely highly suitable (S1), moderately suitable (S2), marginally suitable (S3) and not suitable (NS), were defined based on the most severe limitation(s)[33]. To undertake this classification, land characteristics derived from soil

observations were matched with the crop requirements listed in Table 2 to assign a land suitability class for each soil observation; the so-called matching process. Spatial interpolation between observations was then used to generate suitability maps for different LUTs (to create a continuous surface that covers the whole study area). Since the interpolated variable is ordinal, Thiessen polygons, exact interpolators of nearest neighborhood, were used for this interpolation. This procedure is known as proximity analysis, which assigns the suitability rating of an observation point to the closest area to that point[34].

Mapping of current land use

A Landsat Enhanced Thematic Mapper (ETM+) image was used to map the current land use. The spatial (15 m) and spectral resolutions (eight bands) of the ETM+ images are important characteristics for land-use mapping. Both ERDAS imagine 8.4 and ArcView GIS software were used to derive the land-use map. The ETM+ image was geometrically corrected using geo-coded image of SPOT PAN digitally merged with Landsat TM and originally used by the NSMLUP[10]. Visual interpretation of false color composites of ETM+ Bands 2, 3 and 4 was performed through the digitizing process. The identity of each class was determined through field visits during which the location of 45 randomly selected fields was recorded by Global Positioning System (GPS). The visited fields represent the different land-use classes in the study area, being rangeland, field crops, vegetables, trees and urban areas.

Comparison between potential and current land use

The agreement between potential and current land uses was assessed by overlaying the suitability maps with current land-use map. The purpose of this comparison was to determine areas where the current land use is different from potential land use, i.e., areas where land suitability evaluation results indicated that the land is marginally suitable or not suitable for the type of land use for which it is currently used. In other words, good agreement was given for lands that are classified as highly or moderately suitable for trees and currently cultivated with trees. Marginally suitable land was considered under disagreement category because it might be highly or moderately suitable for another use and the farmer is losing opportunity to improve productivity (yield gap between current and potential use). The farms that show strong limitation to their current use (marginally suitable or not suitable) were identified. Sixteen farms were selected to represent different combinations of suitability classes and current land use and were visited to explore the farmers' improved management practices adopted to overcome these limitations.

Field visits

Of the 50 farms that were located within the study area, 16 farms were visited during four field visits. These farms were selected to represent cases where the land evaluation indicated that the farm is not suitable for certain land use and at the same time the farmer is using the land for that use. The semi-structured interview technique was used to interview 25 farmers who own and/or cultivate the land of the selected farms, having no set of questions or questionnaires. Instead, the interviewer used a checklist of topics for the discussions which were decided in advance. The topics of the checklist include information about land-use type, the dominant limiting factors for the actual land use, the management practices that are adopted by farmers to overcome the limiting factor(s) in the land and to improve productivity, the farmers' assessment of productivity (quantity and trend) of the actual land use and the economic benefits from cultivating the land for that land use.

The discussions could evolve freely, and more questions could arise and be asked as others were being answered, without risking the interview losing its structure[35,36]. This also gives farmers more opportunities to add new points that were not accounted for by researchers. The interviews with farmers concentrated on specific management practices to overcome land-use limitations.

Table 3. Area of each suitability class for each LUT as a percentage of the study area (urban area occupies 6.8% of the total area).

LUTs	S1[1]	S2	S3	NS
Open range	–	79	10	4.2
Improved range	–	63.5	20.6	9.1
Rain-fed barley	–	–	76.7	16.5
Drip-irrigated vegetables	–	55	20.6	17.6
Drip-irrigated trees	1	21.6	48.8	21.8

[1] Suitability classes: S1, highly suitable; S2, moderately suitable; S3, marginally suitable; NS, not suitable.

Revised land suitability evaluation

Land evaluation results were revised based on modified rating of land-use limitations and land qualities. This modification takes into consideration the existing land-use pattern and incorporates the farmers' improved management, according to the following steps:

1. The values for each land characteristic were derived from soil observations located within the selected farms (derived from the 2193 soil observations), and each farm contained many soil observations. The weighted average, based on the area of the farm, of these land characteristics for the selected farms was calculated. These average values were considered as the modified value for which the specified land-use type can be implemented successfully (modified criteria). The farmers indicated comparable management practices among these farms and indicated satisfactory yield.
2. Based on these averages, the ratings of land characteristics were modified. The higher value of weighted

Table 4. Summary statistics of relevant land characteristics over the study area.

Land characteristic	Mean	Minimum	Maximum	Standard deviation
Available water-holding capacity (mm/m)	127	0	213	45.8
Soil depth (cm)	84	0	200	31.7
Slope (%)	2	0	12	1.6
WGPT (degree-days)	366	300	387	16.5
Surface cover percent (%)	11	0	95	11.8

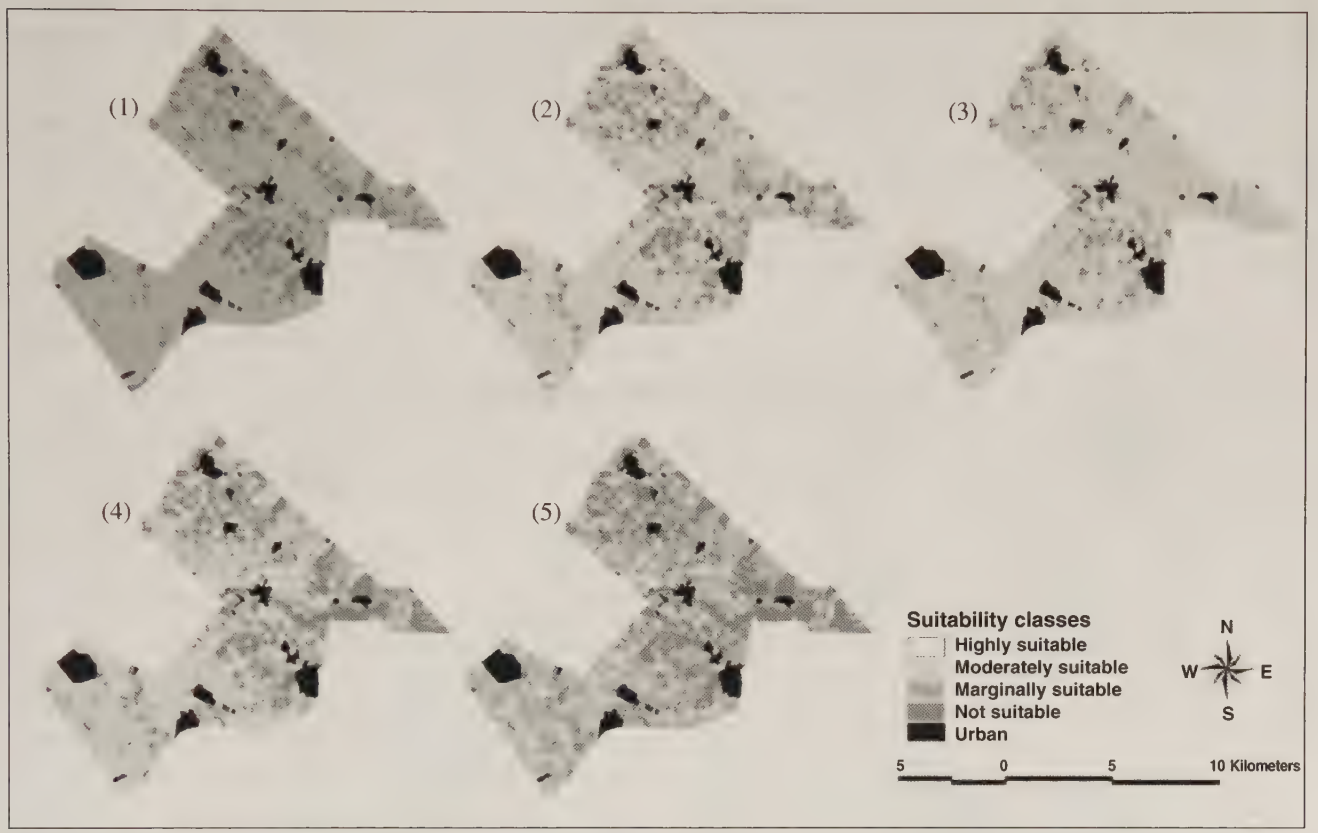

Figure 2. Potential land suitability for (1) rain-fed barley; (2) improved range; (3) open range; (4) drip-irrigated vegetables; and (5) drip-irrigated trees.

average was considered as criterion ranking of highly suitable class and the lower value was considered as criterion ranking for marginally suitable class. For example, the lower limit of soil depth for irrigated trees was 150 cm based on criteria suggested by researchers (Table 2), while the average maximum soil depth under successful cultivation of irrigated trees was calculated to be 103 cm. Therefore, 103 cm was considered as the lower limit for successful cultivation (highly suitable) of irrigated trees using the farmers' management practices.

3. The whole land suitability evaluation process was repeated to take into consideration the modified ratings of land qualities based on field visits and farmers' knowledge.

Results and Discussion

Land suitability

The results based on applying the original land-use requirements show that no land was classified as highly suitable (S1) for open-range, improved-range or irrigated vegetables (Table 3 and Fig. 2). This is because the winter growth potential temperature (WGPT) criterion for S1 is 400 degree-days, and the maximum WGPT in the study area was 387 degree-days (Table 4). No land was classified as highly suitable or moderately suitable for rain-fed barley. This is because the precipitation requirement to classify land to S1 is 250 mm and to S2 is 200 mm, which is higher than the average annual precipitation in the study area (175 mm). A large part of the study area is potentially not

Table 5. Management practices for drip-irrigated vegetables and drip-irrigated trees defined through farmers' interviews and average soil depth for each farm.

Farm No.	Type of crop	Space between rows (m)	Average soil depth (cm)
01	Olive	4	94
02	Olive	5	90
03	Olive	4	93
04	Olive, peaches, nectarine, apricot, apple and pear	5	82
05	Peaches, nectarine and apricot	4	82
06	Olive	5	98
07	Olive	5	88
08	Grape, peaches, nectarine, apricot, apple and pear	4	87
09	Olive	4	95
10	Olive, peaches, nectarine and apricot	4	53
11	Olive, peaches, nectarine and apricot	4	67
12	Pear, peaches, nectarine and apricot	5	66
13	Pear, peaches, nectarine and apricot	5	103
14	Grape, peaches, nectarine, apricot, apple and pear	4	77
15	Tomato and water melon		
16	Tomato and cucumber		

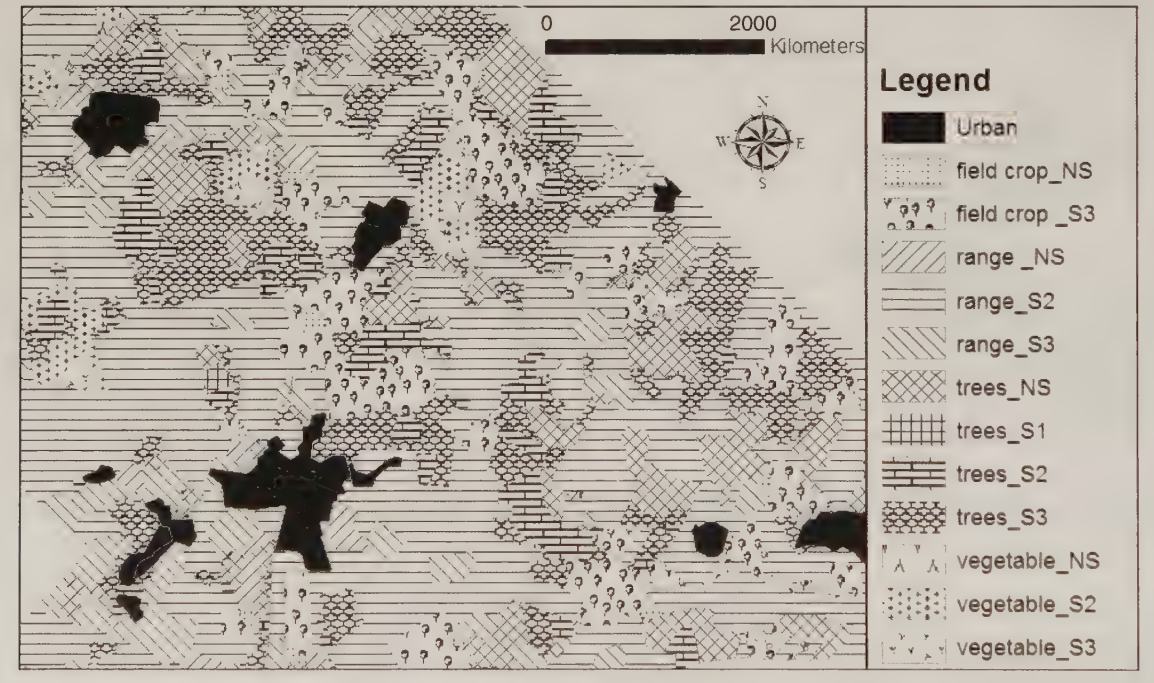

Figure 3. Comparison between current land use and potential land suitability.

suitable for drip-irrigated trees, mainly due to shallow soil depth dominating the study area and high coverage of stones at the soil surface.

Comparing land suitability maps with the current land-use map

The highest agreement between suitability maps and the current land-use map was recorded for open-range (82%), followed by drip-irrigated vegetables (71%), while the agreement was very low in the case of trees (22%) and no agreement was found for field crops (Fig. 3). Variable agreement figures among different land utilizations are due to two factors. The first is the rating of different criteria for each land use and how close this rating is to the actual land-use requirements, and the second is that the farmer's decisions in selecting particular land-use type is not only governed by biophysical factors but incorporate socio-economic dimensions such as marketing, prices, input costs, availability of capital, technical know-how and farming traditions. The information gathered during the field visits were used to identify the farmers' adopted practices

Table 6. Land-use requirements for irrigated vegetables and irrigated trees before and after modification based on farmers' adopted practices.

	Original criteria				Modified criteria			
	Irrigated vegetables		Irrigated trees		Irrigated vegetables		Irrigated trees	
Land characteristic	**S1**[1]	**S2**	**S1**	**S2**	**S1**	**S2**	**S1**	**S2**
Precipitation	NL[2]	NL	NL	NL	NL	NL	NL	NL
WGPT[3]	400	250	>250	NL	NL	NL	>250	NL
AWHC[4]	110	75	110	75	110	75	110	75
Soil depth	100	50	150	100	100	50	103	55
Rill or Gully[5]	1	2	1	2	1	2	1	2
Sheet/Wind/Undiff[5]	1,2	3	1,2	3	1,2	3	1,2	3
Slope	<5	<8	<5	<8	<5	<8	<5	<8
Rock outcrop	<3	<5	<3	<5	<3	<5	<3	<5
Stone at surface	<6	<10	<6	<10	NL	NL	NL	NL
Stone content[6]	<6	<10	<6	<10	NL	NL	NL	NL

[1] Suitability classes: S1, highly suitable; S2, moderately suitable.
[2] NL, not limiting.
[3] WGPT, winter growth potential (summation of degrees >8°C during the coldest months).
[4] AWHC, available water-holding capacity.
[5] Erosion class: 1 = nil, 2 = slight, 3 = moderate, 4 = severe.
[6] Stone content in the surface horizon.

for drip irrigation vegetables and drip irrigation trees (Table 5). Regarding the other LUTs, no specific management practices were identified by farmers and therefore their requirements were not modified.

Revising land suitability evaluation

Based on field visits and farmers' interviews, successful cultivations of vegetables and trees under drip irrigation were recorded in the study area. Current land use and farmers' improved managements that were explored formed a starting point to modify the level of limitation for drip-irrigated vegetables and drip-irrigated trees. Usually, researchers and land-use practitioners will assume the criteria that were suggested in Table 2. This highlights the important role of farmers' knowledge and current land-use data to suggest criteria and land-use types that are more relevant to the target area. These are usually overlooked in conventional land suitability analyses.

Regarding the limitation imposed by the WGPT, drip-irrigated vegetables are cultivated during summer or under plastic tunnels during the winter. Therefore, the WGPT was not considered as a limiting factor according to this assumption. The area of the modified suitability classes was compared with those of the original classification through area cross-tabulation. After the modification of the WGPT criterion, 18% of the area becomes highly suitable and 37% is moderately suitable for vegetables, while before modifying this criterion, the whole 55% of the area was moderately suitable. Based on this modification, more area could be recommended for vegetables, which is in more agreement with the current land use.

Land that was farmed with trees was classified as marginally suitable, mainly due to shallow soil depth and high stone content at the soil surface. However, farmers implement improved management practices to overcome these limiting factors. These include: the use of varieties that have a smaller root system (dwarf species), the implementation of a new tree-training technique (V system), the addition of a high amount of organic matter each year, irrigating the trees three times each week during summer and twice during winter, and the cleaning of rocks and stones from the soil surface. The new technique for the training of trees (V-shape system) was noticed in some farms, where the space between the trees within a row is 2 m only. V-shaped systems often provide higher yield but also need more water than other systems because trees are planted at closer spacing (more intensive farming practice).

According to these assumptions the soil-depth criterion and rock outcrop/stones criterion were modified. Soil depth was modified according to the weighted average of soil

Table 7. Area cross tabulation between suitability classes before and after modifying soil depth and rock outcrop/stones factors for drip-irrigated trees.

	Old classes					
New classes	**S1**	**S2**	**S3**	**NS**	**Urban**	**Sum**
S1[1]	0.8	20.5	2.2	1.1	0	24.6
S2	0	1.1	31.7	1.9	0	34.7
S3	0	0	14.8	4.1	0	18.9
NS	0	0	0	14.9	0	14.9
Urban	0	0	0	0	6.9	6.9
Sum	0.8	21.6	48.7	22.0	6.9	100

[1] Suitability classes: S1, highly suitable; S2, moderately suitable; S3, marginally suitable; NS, not suitable.

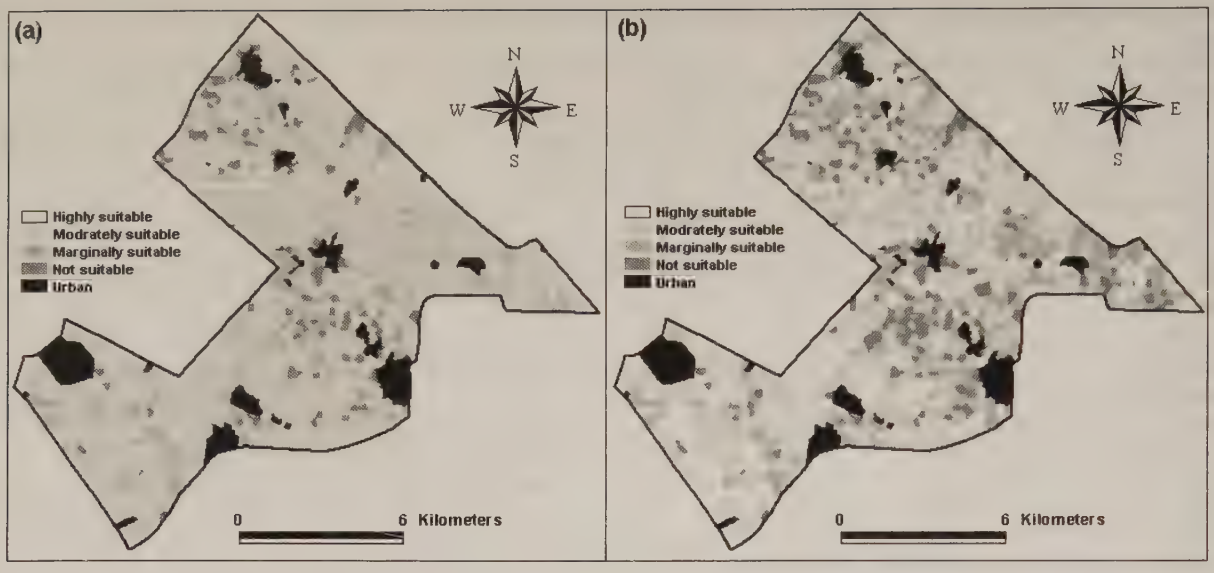

Figure 4. Comparison of land suitability maps for irrigated trees for (a) original criteria and (b) modified criteria.

depth, which was calculated for all farms that were visited. The average of soil depth for each farm was calculated using the observation points that exist in that farm. The weighted average for soil depth in these farms ranges from 55 to 103 cm (Table 5). The higher value of weighted average (103 cm) indicates the criteria ranking for highly suitable class (instead of 150 cm before modification), and lower value of weighted average (55 cm) indicates criteria ranking for moderately suitable class. The stones were not considered a limiting factor because farmers remove stones from their farms if necessary. Table 6 shows the criteria before and after modification, whereas Table 7 shows area cross-tabulation between original suitability classes and suitability classes after modifying the soil depth and rock outcrop/stones factors. In this table, the rows represent suitability classes after modifying the soil depth and rock outcrop/stones factors and the columns represent original suitability classes (without modifications).

The results indicated that 25, 35, 19 and 15% of the total study area becomes highly, moderately, marginally and not suitable, respectively, for irrigated trees as a result of modifying the soil-depth and rock outcrop/stones criteria (Table 7), compared to 1, 22, 49, and 22%, respectively, before modifying these criteria. Generally, there is a shift toward better suitability classes as a result of this modification (Fig. 4). This is logical since the modification follows the farmer's management practices to overcome land-use limitations, which convert more land for better utilization. Based on this modification, more area could be recommended for trees, which is in more agreement with current land use.

The results indicated that based on the modified criteria, which consider the farmers' adopted land-use practices specific to this area, a larger percentage (59%) of the study area is proposed for drip-irrigated trees compared to the area proposed for this utilization using the original criteria suggested by researchers (22%). Furthermore, 18% of the area is considered highly suitable for drip-irrigated vegetables using the modified criteria, while no land was considered highly suitable using the original criteria. Therefore, using the modified criteria, more land could be proposed for drip-irrigated trees and vegetables. This provides a good basis for the decision-making process that takes into consideration the available land resources and their sustainable use and management.

Conclusions

The agreement between current land use and potential land suitability depends on the type of land use under consideration, and in this study it ranged between 82% agreement for open range and no agreement for field crops. This is partially due to the method of suitability calculation and partially due to farmers' adopted technologies to overcome land-use limitations. Potential suitability of land indicated a limited chance for cultivating trees and vegetables under irrigation. However, the current land-use pattern showed that large areas are utilized in this way. Field visits and farmers' interviews indicated some management practices that are adopted by farmers, such as the cultivation of vegetables in summer or in winter under plastic tunnels to overcome the limitation imposed by low winter temperature. Other practices were implemented to overcome limitations imposed by soil and stone content to improve land suitability for irrigated trees. These include the use of dwarf varieties, a special training technique for trees, the addition of organic matter, a more frequent irrigation schedule and the removal of stones from the land surface. These farmers' adopted techniques were used as a starting point to change the suitability criteria for the two utilization types. As a result of modifying these criteria, 18% and 24% of the area was re-classified as highly

suitable for vegetables and trees, respectively. The revised land suitability results indicated that more land could be allocated for irrigated trees and vegetables, which is in agreement with the current land-use pattern in the study area. The approach followed in this study incorporates farmers' knowledge and provides the basis for undertaking wise decisions about the integrated use and management of land resources.

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Renewable Agriculture and Food Systems: 26(4); 297–316 doi:10.1017/S1742170511000111

Comparing conventional and organic olive groves in central Greece: plant and bird diversity and abundance

Alexandra Solomou and Athanassios Sfougaris*

Laboratory of Ecosystem and Biodiversity Management, Department of Agriculture, Crop Production and Rural Environment, University of Thessaly, Fytokou Str., N. Ionia, 384 46, Volos, Greece.
*Corresponding author: asfoug@agr.uth.gr

Accepted 13 February 2011; First published online 1 April 2011 **Research Paper**

Abstract

The present study was conducted in Magnesia Prefecture, central Greece, during the period May–June 2007. It aimed at the comparison between conventional and certified organic olive groves with regard to olive and olive oil production, diversity of plants (herbaceous and woody) and diversity and abundance of avifauna. Correlations between variables within herbaceous plants (linear regression) and woody plants (Principal Component Analysis), and the role of integration time of olive groves to the organic system were investigated. Also, finding easily measurable parameters indicating high bird diversity levels within organic and conventional management systems was a main target of the study. According to our findings, neither edible olive yield nor olive oil yield showed significant differences between conventional and certified organic olive groves. There is an increasing trend for alpha and beta diversity of herbaceous plant species, woody plant beta diversity, density and cover of woody plants, and density of breeding birds in certified organic olive groves (10 years) in comparison with conventional ones. The effect of time since the adoption of organic procedures is very important and produces benefits for the biodiversity. In the total olive groves 15 insectivorous, six granivorous and three insectivorous/granivorous birds species were recorded. Nine bird species distinguished by Ward's hierarchical clustering were identified as typical (indicator value, IndVal > 50%) of specific farming systems. Among them, the Eurasian jay, associated with the 10-year certified organic olive groves, and the common cuckoo, Orphean warbler and Red-backed shrike, associated with the 6-year certified organic olive groves, should be regarded as characteristic species (IndVal > 70%). Conclusively, organic farming favors some aspects of diversity of herbaceous and woody plants of olive grove ecosystems. On the contrary, similar effects on breeding bird diversity and density were not clearly recorded. However, breeding bird density proved a good indicator of their richness.

Key words: biodiversity, olive groves, conventional, organic, bioindicators

Introduction

Economically, the olive tree is the most important fructiferous tree grown in Greece and at the same time is ranked third worldwide. Half of the Greek farmers have included the cultivation of olive trees in their agricultural activities[1]. It is well adapted to a wide range of climatic conditions and is drought resistant[2].

Many researchers have stated that olive grove ecosystems are more stable than other agricultural ecosystems[3–6]. Cirio[7] argues that this stability may be due to the general stability of the whole olive grove environment, the low level of infection, the resistance against damage caused by pests and the abundance of beneficial arthropod fauna. Generally, the organic olive-farming system seems to be clearly superior to the integrated and conventional ones with respect to biodiversity[8].

The development of intensive agriculture has focused at maximizing the production, but resulted in severe environmental degradation, as well as degradation of product quality. In conventional farming some objectives are the increase of production, profits through monoculture and intensive soil treatment, irrigation and use of agrochemicals and fertilizers. It should be noted that conventional agriculture is inferior compared to organic agriculture regarding soil ecology and fertility, and this has resulted in the reduction of diversity and abundance of soil organisms[9].

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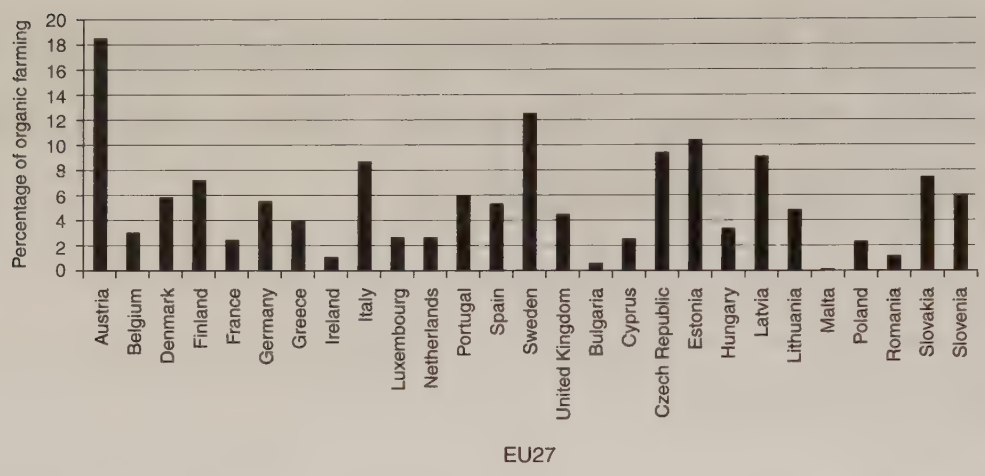

Figure 1. Organic farming (%) in the EU27 in 2009.

The adoption of modern conventional agriculture is considered to be among the main threats to global biodiversity. A dramatic reduction in the number and abundance of many species associated with farmland has been reported for the last quarter of the 20th century. This reduction leads to increasing concern regarding the sustainability of current intensive production practices[10].

Organic farming is a low-intensity farming system implemented through the use of biological and mechanical cultivation methods, excluding the use of chemicals and contributing to biodiversity conservation[11,12]. According to European Council Regulation (EC) 834/2007 and Commission Regulation (EC) 889/2008, the aims of an organic production system are to enhance the biological diversity and activity, maintain long-term soil fertility, minimize non-renewable sources and all pollutants and treat agricultural products in a way to maintain the organic integrity and vital substances[13].

In 2009, the total organic area accounted for 4.72% of the total agricultural area in the EU27. The highest proportions of organic area were recorded in Austria (18.5% of the total agricultural area), Sweden (12.56%) and Estonia (10.49%). In Greece, the percentage of organic farming was 3.94% of the total agricultural area[14,15] (Fig. 1).

In Europe, many studies have been conducted regarding organic farming and wildlife[10,16–26]. Specialized research with regard to the effects of management of agricultural ecosystems on the flora[27–32], avifauna[33–36], arthropods[37–40], butterflies[41] and spiders[42,43] has been accomplished.

The role of birds as biodiversity indicators has been widely recognized in biodiversity studies[44–47]. Bird communities representing the total biodiversity, were considered to be the most appropriate biodiversity indicators because they are easily identifiable, their classification and systematics are well established and their ecology and behavior have been thoroughly studied, making the risk of misinterpretations low. Birds also tend to be high in the food chain and this would help to detect any 'signals' that accumulate through the chain[44].

In Greece there are a few studies concerning various aspects of biodiversity in conventional and organic farming systems[48–52]. However, there is a lack of comparative studies on biodiversity between conventional and certified organic olive groves in Greece[53–56].

The main aim of our study was to assess the effects of conventional and organic farming systems on some aspects of biodiversity of olive grove ecosystems in a typical Mediterranean environment. Plant and bird communities and species were used as a tool to indicate the effects of different management schemes on olive groves. The specific objectives of the study were to compare conventional and certified organic olive grove ecosystems on the basis of: (a) their yield, (b) plant diversity (herbaceous and woody vegetation), (c) diversity and abundance of avifauna, (d) finding easily measurable parameters indicating bird diversity within organic and conventional management systems and (e) the role of integration time of olive groves into the organic farming procedure. All the above objectives are investigated and conclusions are drawn under the restriction of the one-year duration of the study.

Materials and Methods

Study area

Among the olive grove farms of western Magnesia Prefecture, central Greece (39°06′54.80″N, 22°55′16.32″E) a set of 16 farms was randomly selected (eight certified organic and eight conventional). The subset of conventional olive groves included four sprayed and four non-sprayed farms (C1–C4 and C5–C8 farms, respectively) and the subset of organic ones was divided into two groups (four farms in each group), one certified organic for 6 years and one for 10 years (O1–O4 and O5–O8 farms, respectively) (Fig. 2). The area (mean ± SE) of farms was respectively (in ha): 39.25 ± 20.95, 43.00 ± 21.11, 29.25 ± 18.64 and 31.00 ± 12.74. The sampling farms were at least 200 m away from each other and the sampling points 100 m away from the farm edge to avoid farm edge effects. The

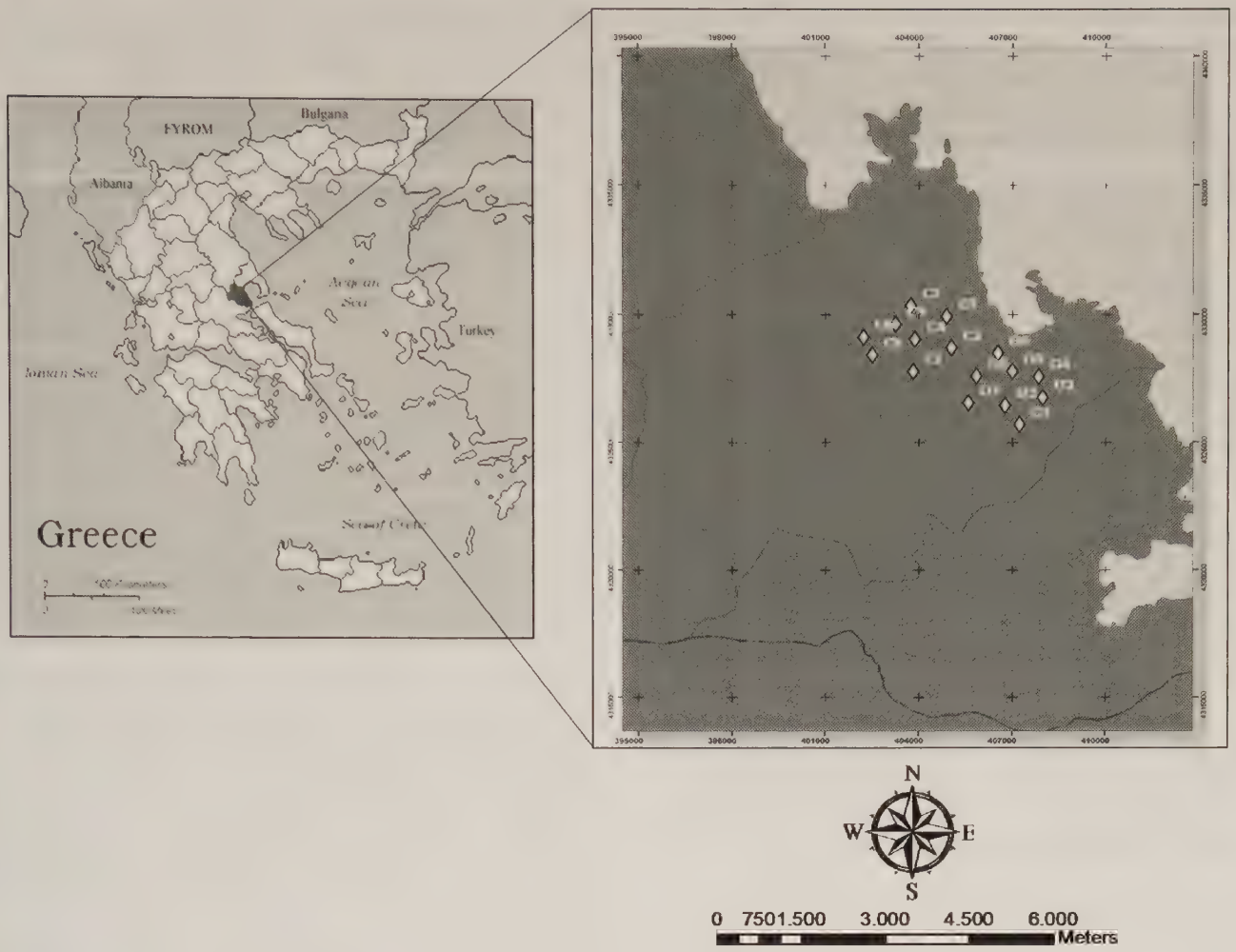

Figure 2. Study area (western Magnesia Prefecture, central Greece).

sampling farms are surrounding by olive groves, pastures and natural ecosystems composing a diverse landscape.

The characteristics and management practices applied to the selected farms are presented in Table 1. The purpose of this selection was to minimize the influence of 'external' environmental factors and to allow a better comparison among the four farm management systems.

The study area is included in the Quercetalia ilicis vegetation zone, and Quercion ilicis and Oleo-Ceratonion subzones. The main rock substrate of the study area is metamorphic schist. The climate is characterized as continental with relatively cold winters and hot and dry summers. The mean annual temperature is 18.8°C, the warmest month is July and the coldest January and February (Fig. 3). The mean annual precipitation reaches 350.3 mm and the mean annual air humidity 62%, ranging for the winter between 69 and 77% and for the summer between 55 and 66%[57].

Plant and bird survey

The sampling of herbaceous vegetation was carried out in May 2007 in randomly selected plots of 0.25 m^2 (0.5 m × 0.5 m), where the number of species, frequency of occurrence and their biomass were estimated[58]. Woody vegetation was inventoried during the same period in randomly selected sampling plots of 100 m^2 (10 m × 10 m). In each plot, the number of species, the number of individuals per species (density) and their coverage were measured[59].

The avifauna was censused from early May until the middle of June 2007 so as to include the breeding period[60,61]. For bird counting, the point count method was followed[62]. The counts were conducted from early morning until 10.30 am and only during the days without rain or wind. Only breeding pairs, represented by territorial males, in each plot of 50 m radius were recorded by two observers. Each count lasted for 10 min. The species diversity and abundance, expressed as breeding pairs per ha (bp/ha), were estimated[63–65]. The number of sampling plots for each treatment (management practice) was: 60 in the 10-year certified organic olive groves, 60 in the 6-year certified organic olive groves, 90 in the sprayed conventional ones and 90 in the non-sprayed conventional ones for each parameter (herbaceous plants, woody plants and birds).

Table 1. General characteristics and management practices applied to the olive grove farms surveyed.

	Organic (6 years)	Organic (10 years)	Conventional (sprayed)	Conventional (non-sprayed)
Average number of olive trees per hectare	200	200	200	200
Age of olive groves	150–170	150–170	150–170	150–170
Variety of olive groves	Amfissa, Pelion	Amfissa, Pelion	Amfissa, Pelion	Amfissa, Pelion
Years of enrolment	2001	1997		
Type of soil	Clay	Clay	Sandy clay loam	Sandy clay loam
Manure (kg per tree)	–	50	–	–
Fertilizers				
Potassium (kg per tree)	1–1.5	1–1.5	–	–
Calciferous nitric ammonia (kg per tree)	–	–	2	2
Borax (g per tree)	200	200		
Weed control	Grass cutter	Sheep grazing	Herbicides	Soil treatment, shrub cutters

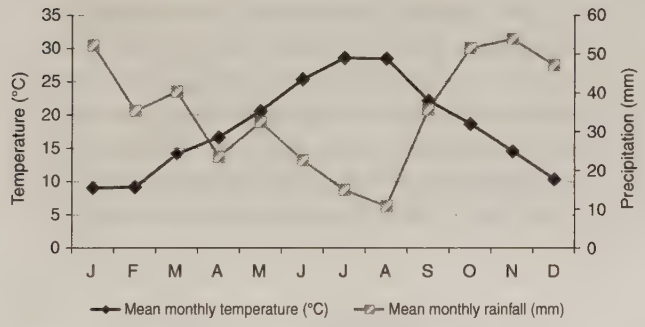

Figure 3. Ombrothermic diagram of the study area.

Statistical analysis

Vegetation and bird data were evaluated for normality and homogeneity with the Kolmogorov–Smirnov and Shapiro–Wilk tests. Data were transformed using $\log_{10}(x+1)$ when necessary to meet normality assumptions[66]. For the analysis of vegetation and bird data, the parametric one-way analysis of variance was used. Turkey's HSD (Honestly Significantly Different) pairwise comparison tests were used with $P<0.05$. Correlations between variables within each taxonomic group were examined using Pearson correlation coefficients[67]. Alpha, beta and gamma diversity were calculated[68]. Alpha diversity refers to the diversity within a particular area or ecosystem, and is expressed by the number of species (species richness, Shannon–Weiner index, Simpson index and Berger–Parker index) and evenness (evenness index) in that ecosystem. We also examined the similarity in species diversity (Jaccard index and Sorensen index) between the different olive grove types expressing the beta diversity. Gamma diversity is a measure of the overall diversity of the different ecosystems within a region, whereas Hunter[69] defines gamma diversity as 'geographic-scale species diversity'. All relationships between herbaceous plant variables were analyzed by using the Pearson's product moment correlation coefficient r, whereas the description of correlation between woody plant variables was analyzed by using Principal Component Analysis (PCA)[70].

For the definition of biotic indicators of bird species richness on organically and conventionally managed olive groves the calculation of linear regressions between the goal parameter (species richness) and potential indicator parameters was realized[67,71]. High positive correlation of a potential indicator with the goal parameter is considered as a measure of indicator reliability ($R^2>0.5$, $P<0.05$)[72]. Seven parameters were chosen as potential indicators of bird species richness: (1) density of all breeding birds, (2) number of herbaceous plant species, (3) biomass production of herbaceous plant species, (4) number of woody plant species, (5) density of the woody plants, (6) percentage cover of woody plant species and (7) altitude. The above indicators were used for predicting the variability of bird diversity within each management system. Accordingly, the correlation between potential indicators and the goal parameter for organic and conventional olive groves was calculated separately. All data analyses were performed using PASW version 18.0 software[73].

In order to study changes in generic composition, we used the (indicator value IndVal) method of Dufrêne and Legendre[74]. We used Ward's clustering method to group hierarchically the records of birds of the point counts into clusters, expressing the different bird community of each farming system. We also identified the typical species characterizing each of the clusters using the IndVal procedure. These calculations were carried out using the IndVal software[75]. A species is considered a 'symmetrical indicator' (IndVal > 50%) for one cluster, when it is present in >70% of the sites of the cluster and when >70% of its individuals occur in the cluster. A random reallocation procedure (999 iterations) of sites among site groups was used to test IndVal significance (alpha = 0.01).

Results

Olive and olive oil production

In the study area during the production period 2006–07, the mean edible olive yield in conventional olive groves reached 56.8 ± 0.99 kg tree^{-1}, while in the certified organic

Table 2. Olive and olive oil yield (kg per tree) in organic and conventional olive groves of the study area.

		Mean ± SE	*F*	*P*
Organic olive groves	*Edible olive yield*	51.5 ± 3.94		
Conventional olive groves		56.8 ± 0.99	1.69	0.20
Organic olive groves	*Olive oil yield*	10.0 ± 0.42	2.66	0.12
Conventional olive groves		11.1 ± 0.52		

ones the yield was $51.5 \pm 3.94\,kg\,tree^{-1}$. The olive oil yield in conventional olive groves was, on average, $11.1 \pm 0.52\,kg\,tree^{-1}$, whereas in the certified organic ones it was $10.0 \pm 0.42\,kg\,tree^{-1}$. However, neither edible olive yield ($P = 0.20$) nor olive oil yield ($P = 0.12$) showed significant statistical differences between conventional and certified organic olive groves[76] (Table 2).

Herbaceous plants

Frequency of occurrence. In total, in the olive groves studied [certified organic (10 years), certified organic (6 years), conventional (non-sprayed), conventional (sprayed)] 56 species of herbaceous plants belonging to 20 families were recorded (Table 3).

Independently of the management practices applied, Poaceae and Asteraceae were the most important families in terms of number of plant species structuring the herbaceous plant community of the olive groves studied, including 30 and 23% of the total plant species recorded, respectively. All the families represented by a unique species were grouped into one category. Other families recorded include Zygophyllaceae, Hypericaceae, Chenopodiaceae, Linaceae, Liliaceae, Rosaceae, Cistaceae, Lamiaceae, Dispacaceae, Scrophullariaceae, Amaranthaceae, Malvaceae and Apiaceae (%) (Fig. 4).

The most frequently occurring plants in each farming system were *Daucus carota* (28.3%) in the 10-year certified organic olive groves, *Aegilops geniculata* (55%) in the 6-year certified organic ones, *D. carota* and *Scabiosa stellata* (20%) in the sprayed conventional ones and *S. stellata* (30%) in the non-sprayed conventional ones.

Alpha, beta and gamma diversity. The 10-year certified organic olive groves exhibited the highest values of species richness (38), Shannon diversity index (0.28), Simpson index (0.26), evenness index (0.27) and Berger–Parker index (0.17), whereas the sprayed conventional olive groves had the lowest values (15, 0.03, 0.04, 0.04 and 0.10, respectively) (Table 4).

Concerning the alpha diversity of herbaceous plants, significant statistical differences of the species richness, Shannon diversity, Simpson, Evenness and Berger–Parker indexes ($P < 0.05$) were found between the different management systems.

The highest values of the Jaccard and Sorensen indexes were found between the 10-year certified organic olive groves and the 6-year certified organic ones (0.59 and 0.74, respectively), whereas the lowest value was estimated between the 10-year certified organic olive groves and the sprayed conventional ones (0.18 and 0.31, respectively) (Table 5). As concerning the total number of herbaceous species of all olive groves it was 56, representing the gamma diversity.

Biomass production

The highest biomass production of herbaceous plants ($g\,m^{-2}$) was estimated in the 10-year certified organic olive groves (1.53 ± 0.02) and the lowest was in the sprayed conventional olive groves (0.88 ± 0.04). Significant statistical differences ($F = 53.10$ and $P = 0.00$) were detected in the biomass produced among the different types of olive groves of the study area (Fig. 5).

Species richness and diversity relationships

A very strong linear correlation was found between the number of species of herbaceous plants and the Shannon diversity index ($r = 0.96$ and $P = 0.00$) (Fig. 6), whereas a moderate linear correlation was found between the Shannon diversity index and biomass ($r = 0.50$ and $P = 0.00$). A weak linear correlation was detected between the number of species of herbaceous plants and biomass ($r = 0.42$ and $P = 0.00$), the number of species of herbaceous plants and altitude ($r = 0.23$ and $P = 0.00$), biomass and altitude ($r = 0.17$, $P = 0.00$) and the Shannon diversity index and altitude ($r = 0.22$ and $P = 0.00$).

Woody plants

Frequency of occurrence. A total number of 17 species of woody plants were recorded in all types of olive groves of the study area [certified organic (10 years), certified organic (6 years), conventional (non-sprayed), conventional (sprayed)].

The most frequently occurring woody species were: *Olea europaea* var. *sylvestris* (55.2%) in the certified organic (10 years), *O. europaea* var. *sylvestris* (42.6%) and *Vitex agnus castus* (42.6%) in the certified organic (6 years), *Pistacia terebinthus* (45.0%) in the conventional (sprayed) and *Pistacia lentiscus* (36.1%) in the conventional (non-sprayed) (Table 6).

Alpha, beta and gamma diversity. As regards the woody plant alpha diversity, the highest value of the species richness (17) was estimated in the sprayed conventional olive groves, whereas the highest values of Shannon diversity index (0.31), Simpson index (0.26), evenness index (0.29) and Berger–Parker index (0.21) were estimated in the 6-year certified organic olive groves. Significant statistical differences in the species richness, Shannon diversity, Simpson, evenness and Berger–Parker

Table 3. Frequency of occurrence (%) of the herbaceous plant species in the olive groves under different management system (asterisk (*) denotes significant difference in the frequency of occurrence of herbaceous plants among farming systems).

Species	Organic (10 years) olive groves	Organic (6 years) olive groves	Conventional (sprayed) olive groves	Conventional (non-sprayed) olive groves	*F*	*P*
Briza maxima	11.7*	1.7	–	–	6.22	0
Avena sterilis	18.3	6.7	5	10	2.37	0.07
Tribulus terrestris	5	1.7	–	–	2.05	0.1
Echium vulgare	3.3	1.7	–	–	1.23	0.29
Piptatherum miliaceum	3.3	1.7	–	–	1.23	0.29
Medicago lupulina	3.3	–	–	–	2.03	0.11
Heliotropium europaeum	8.3	1.7	–	3.3	2.44	0.06
Aegilops ovata	3.3	–	–	–	2.03	0.11
Trifolium angustifolium	8.3*	1.7	–	–	4	0
Hypericum perforatum	6.7*	1.7	–	–	2.98	0.03
Chenopodium album	1.7	1.7	–	–	0.66	0.57
Linum usitatissimum	3.3	1.7	–	–	1.23	0.29
Parietaria officinalis	8.3*	–	–	–	5.36	0
Sorghum halepense	1.7	1.7	–	1.7	0.33	0.8
Vicia pannonica	3.3	–	–	–	2.03	0.11
Cynosurus echinatus	3.3	1.7	–	–	1.23	0.29
Setaria viridis	–	1.7	–	–	1	0.39
Xanthium spinosum	13.3*	3.3	8.3	–	3.5	0.01
Aegilops triuncialis	3.3	1.7	–	–	1.2	0.29
Muscari comosum	1.7	1.7	–	–	0.66	0.57
Sanguisorba magnoli	1.7	5	–	–	2.05	0.1
Cistus incanus	6.7	1.7	–	3.3	1.72	0.16
Daucus carota	28.3	23.3	20	21.7	0.43	0.73
Hordeum murinum	23.3	25*	3.3	8.3	5.79	0
Chrysanthemum segetum	1.7	5	–	–	2.05	0.1
Satureja nervosa	8.3*	–	–	5	3.17	0.02
S. stellata	8.3	23.3	20	30*	3.1	0.02
Pallenis spinosa	5*	–	–		3.1	0.02
Chrysanthemum coronarium	10	–	–	11.7*	4.83	0
Erigeron canadensis	11.7*	–	–	–	7.79	0
Bromus tectorum	10	10	6.7	–	2.16	0.09
Sinapis arvensis	16.7	15	10	5	1.62	0.18
Verbascum undulatum	1.7	–	–	–	1	0.39
Sonchus oleraceus	11.7*	3.3	–	–	5.29	0
Dorycnium germanicum	3.3	–	–	1.7	1.23	0.29
Hieracium maculatum	–	–	–	1.7	1	0.39
Trifolium tomentosum	–	–	–	3.3	2.03	0.11
Cynodon dactylon	–	–	6.7	8.7*	2.81	0.04
Amaranthus albus	–	–	5*	–	3.1	0.02
Vicia cracca	–	–	–	5*	3.1	0.02
Gastridium ventricosum	–	–	–	1.7	1	0.39
Sisymbrium officinale	3.3	–	–	5	1.85	1.13
Sonchus asper	–	–	1.7	1.7	0.99	0.39
Lolium rigidum	1.7	3.3	6.7	–	1.75	0.16
Carduus pycnocephalus	1.7	3.3	6.7	–	1.75	0.16
Setaria verticillata	31.7*	–	–	–	27.34	0
Hordeum villosum	–	28.3*	–	6.7	16.04	0
Lolium perenne	–	–	13.3*	5	9.07	0
A. geniculata	–	55*	–	–	53.1	0
Chamomilla recutita	3.3	41.7*	1.7	–	32.51	0
Papaver rhoeas	–	6.7*	–	6.7*	2.81	0.04
Tragopogon pratensis	–	–	1.7	8.3*	4	0
Malva sylvestris	–	25*	–	8.3	12.42	0
Anthemis tinctoria	–	–	–	11.7*	7.79	0
Reichardia picroides	–	–	–	6.7*	4.21	0
Rapistrum rugosum	–	15*	6.7	–	6.3	0

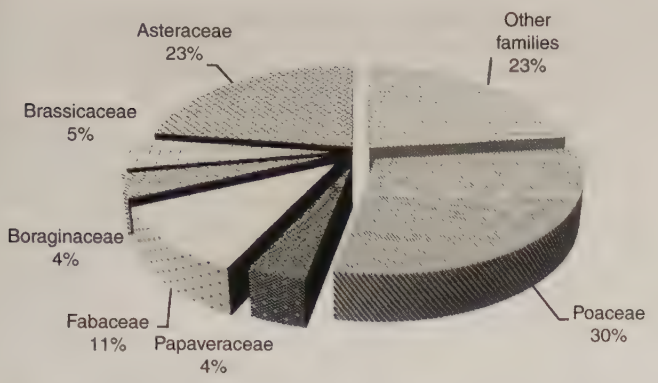

Figure 4. Families of herbaceous plants (%) recorded in the olive groves of the study area.

indexes were found ($P < 0.05$) among the different management systems (Table 7).

As concerning the Jaccard index and Sorensen index, their highest values were calculated between the 10-year certified organic olive groves and the 6-year certified organic olive groves (0.92 and 0.9, respectively) (Table 8). The total number of species recorded in all olive groves was 17, which represent the gamma diversity.

Density. The highest density (individuals per ha) of woody plants (7.00 ± 0.32) was recorded in the 10-year certified organic olive groves, whereas the lowest density (2.91 ± 0.16) was recorded in the sprayed conventional olive groves. Significant statistical differences were detected ($F = 55.18$ and $P = 0.00$) in the density of woody plants among the farming treatments (Fig. 7).

Cover. The highest percentage (%) cover of woody plants was recorded in the 10-year certified organic olive groves (0.60 ± 0.02), whereas the lowest percentage cover was in the sprayed conventional olive groves (0.34 ± 0.01). Significant statistical differences ($F = 25.81$ and $P = 0.00$) in the percentage of woody plant cover among the different types of olive groves were detected (Fig. 8).

Relationships between variables of woody plants. According to the PCA results (Table 9) five axes explain the whole variability observed among the five variables of woody plants tested (number, density, Shannon diversity index, percentage of cover of woody plant species and altitude). The first two axes (components) together explain 75.56% of the variance in variables of woody plants relation (component 1 = 57.48% and component 2 = 18.07%). For component 1, correlation between the number, density and Shannon diversity index of woody plant species was detected, whereas for component 2 moderate correlation between percentage cover and altitude was observed (Fig. 9).

The PCA resulted in the following equalization: for the component 1, 0.95 number of species + 0.91 Shannon diversity index + 0.86 density + 0.43 cover + 0.43 altitude; and for the second component, − 0.20 number of species − 0.30 Shannon diversity index − 0.02 density + 0.67 cover + 0.54 altitude.

Breeding birds

Frequency of occurrence of breeding bird species. In total 24 species of breeding birds were recorded in the olive groves under different farming systems [certified organic (10 years), certified organic (6 years), conventional (non-sprayed), conventional (sprayed)] (Table 10). Four of them are Species of Conservation Concern (SPEC) according to the Birds Directive (2009/147/ EC, former 79/409). More specifically, the Olive-tree warbler (*Hippolais olivetorum*) and Red-backed shrike (*Lanius collurio*) are included in the Annex I of the Directive and the European turtle dove (*Streptopelia turtur*) and Common blackbird (*Turdus merula*) in the Annex II/2. A clear trend in the number of breeding bird species in relation to the specific farming system was not detected ($F = 0.78$ and $P = 0.50$). All olive grove types as a whole exhibited high ornithological importance, as three and eight species of unfavorable conservation status concentrated or not in Europe (SPEC 2 and SPEC 3) were recorded, respectively (Table 10).

On the basis of their feeding preferences (food category) only slight differences in the number of bird species per food category among the different farming systems were observed. More specifically, 15 insectivorous, six granivorous and three insectivorous/granivorous bird species were observed in the study area. Among them nine insectivorous species were recorded in the 10-year certified organic olive groves and ten insectivorous species in each of the rest olive grove types.

Regarding the granivorous birds, six of them were recorded in the non-sprayed conventional olive groves and five species in each of the rest olive grove types. Furthermore, three insectivorous/granivorous species were observed in the 10-year certified organic olive groves and two in each of the other farming systems.

The Eastern olivaceous warbler was the most frequently occurring species in the study area, accounting for 35% of the frequency of occurrence in the 10-year certified organic olive groves, 41.7% in the 6-year certified organic ones, 38.3% in the sprayed conventional ones and 41.4% in the non-sprayed conventional ones.

Species diversity. Almost the same number of species was found in all types of olive groves. On the basis of diversity indexes the highest bird diversity was recorded in the 6-year certified organic olive groves [Shannon diversity index (0.21), Simpson index (0.20), Evenness index (0.21) and Berger–Parker index (0.19)]. No significant statistical differences in the species richness, Shannon diversity, Simpson, Evenness and Berger–Parker indexes, were detected among the olive groves of different farming systems ($P > 0.05$) (Table 11).

As concerning the Jaccard index and Sorensen index, their highest values were calculated between the non-sprayed conventional olive groves and the sprayed conventional ones (1.0 in both cases) (Table 12). The overall number of breeding bird species recorded in the olive

Table 4. Values of alpha diversity indexes of the herbaceous vegetation in olive groves under different management systems.

Index	Organic (10 years)	Organic (6 years)	Conventional (non-sprayed)	Conventional (sprayed)	*F*	*P*
Species richness	38a*	31a	25b	15c	41.88	0.00
Shannon–Wiener	0.28a	0.24a	0.15b	0.03c	48.92	0.00
Simpson	0.26a	0.21ab	0.18b	0.04c	39.33	0.00
Evenness	0.27a	0.22ab	0.18b	0.04c	43.06	0.00
Berger–Parker	0.17a	0.14a	0.15a	0.10b	9.09	0.05

* Different letters (row) mean statistically significant differences for significance level $P < 0.05$.

Table 5. Values of beta diversity indexes of the herbaceous vegetation in olive groves under different management systems.

	C_j*	C_s**
Organic (10 years)–organic (6 years)	0.59a***	0.74a
Organic (10 years)–conventional (non-sprayed)	0.25c	0.40c
Organic (10 years)–conventional (sprayed)	0.31b	0.48b
Organic (6 years)–conventional (non-sprayed)	0.28c	0.44c
Organic (6 years)–conventional (sprayed)	0.27c	0.43c
Conventional (non-sprayed)–conventional (sprayed)	0.25c	0.40c

* C_j, Jaccard index; ** C_s, Sorenson index; *** different letters (column) mean statistically significant differences for significance level $P < 0.05$.

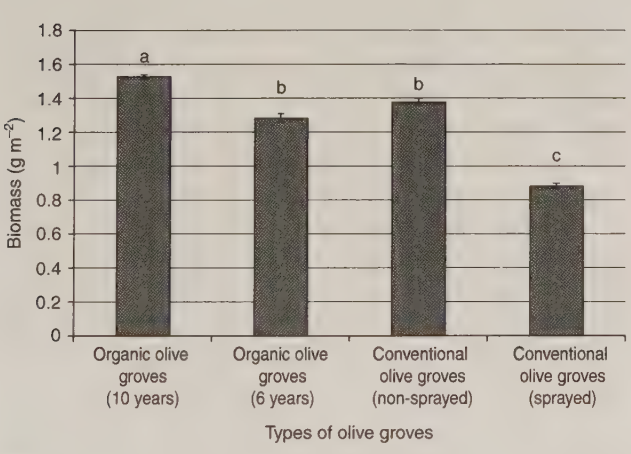

Figure 5. Herbaceous plant biomass production (g m^{-2}) in the different types of olive groves (different letters mean statistically significant differences for significance level $P < 0.05$).

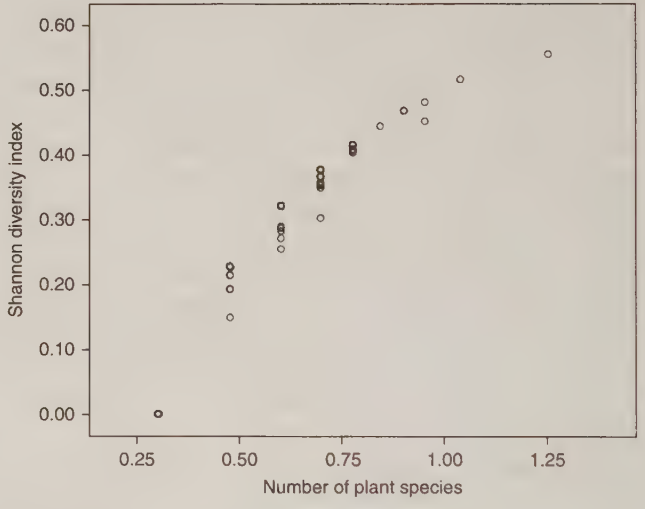

Figure 6. Linear correlation between the number of plant species and the Shannon diversity index.

groves of all management systems (24) represents the gamma diversity.

Density. In Fig. 10, the average number of breeding pairs (bp) of birds per hectare (density) in the different management systems of olive groves are presented. The highest density of breeding birds (bp/ha) was recorded in the 10-year certified organic olive groves (7.07 ± 0.3) and the lowest one in the sprayed conventional olive groves (4.9 ± 0.16). However, no significant statistical differences ($F = 1.82$ and $P = 0.14$) in the breeding density among the different types of farming systems were recorded.

Biotic and abiotic indicators of bird species richness. The density of breeding birds proved to be the best predictor of the number of breeding bird species within certified organic and conventional olive groves, explaining 71 and 93% of the number of breeding species variance, respectively ($R^2 = 0.71$ and 0.93) (Fig. 11a,b). Also, number and biomass production of herbaceous species, number, density and cover of woody species, as well as altitude could not be used to predict the numbers of breeding bird species (Table 13).

Typical bird species. Among the 24 species included in the analysis, nine had a significant IndVal index at one or several levels of the typology (Fig. 12 and Table 14). Two species [Eurasian Jay (100.00)–Northern wheatear (50.00)] had their maximum value in the 10-year certified organic olive groves, three species [Common cuckoo (100.00)–Orphean warbler (75.00)–Red-backed shrike (75.00)] in the 6-year organic ones, four species

Table 6. Frequency of occurrence (%) of woody plant species in the different olive grove types (asterisk (*) denotes significant difference in the frequency of occurrence of woody plants among farming systems).

Species	Organic (10 years)	Organic (6 years)	Conventional (sprayed)	Conventional (non-sprayed)	*F*	*P*
Origanum vulgare	10.3*	1.6	–	4.9	3.44	0.017
Arbutus unedo	1.7	1.6	–	24.6*	13.75	0.00
Cercis siliquastrum	1.7	–	20.0*	14.8	7.48	0.00
C. incanus	1.7	36.1*	10.0	32.8	11.99	0.00
Hedera helix	34.5*	–	–	14.8	17.84	0.00
Erica arborea	1.7	36.1*	11.7	19.7	9.72	0.00
Juniperus oxycedrus	32.8*	–	20.0	9.8	9.86	0.00
Pyrus amygdaliformis	39.7*	27.9	16.7	14.8	4.296	0.006
Prunus spinosa	34.5*	–	–	13.1	18.30	0.00
P. terebinthus	24.1	23.0	45.0*	18.0	4.38	0.00
P. lentiscus	–	32.8*	20.0	36.1	10.21	0.00
O. europaea var. *sylvestris*	55.2*	42.6	25.0	29.5	5.07	0.00
Quercus conferta	–	13.1*	6.7	3.3	3.49	0.01
Quercus coccifera	50	37.7	26.7	32.8	2.47	0.06
Rubus fruticosus	–	19.7*	3.3	4.9	7.43	0.00
Thymus vulgaris	36.2*	–	–	19.7	18.55	0.00
V. agnus castus	–	42.6*	3.3	13.1	23.26	0.000

Table 7. Values of alpha diversity indexes of the woody vegetation in olive groves under different management systems.

Index	Organic (10 years)	Organic (6 years)	Conventional (non-sprayed)	Conventional (sprayed)	*F*	*P*
Species richness	13a*	12a	12a	17b	22.46	0.00
Shannon–Wiener	0.29a	0.31a	0.29a	0.19b	17.75	0.00
Simpson	0.23ab	0.26a	0.24ab	0.20b	4.29	0.00
Evenness	0.26a	0.29a	0.27a	0.21b	8.71	0.00
Berger–Parker	0.17a	0.21a	0.16a	0.14b	7.21	0.05

* Different letters (row) mean statistically significant differences for significance level $P < 0.05$.

Table 8. Values of beta diversity indexes of woody vegetation in olive groves under different management systems.

	C_j*	C_s**
Organic (10 years)–organic (6 years)	0.92a***	0.95a
Organic (10 years)–conventional (non-sprayed)	0.47c	0.64c
Organic (10 years)–conventional (sprayed)	0.76b	0.86b
Organic (6 years)–conventional (non-sprayed)	0.71b	0.83b
Organic (6 years)–conventional (sprayed)	0.70b	0.82b
Conventional (non-sprayed)–conventional (sprayed)	0.70b	0.82b

* C_j, Jaccard index; ** C_s, Sorenson index; *** different letters (column) mean statistically significant differences for significance level $P < 0.05$.

[Common linnet (50.00)–Pied flycatcher (50.00)–Whinchat (50.00)–Eurasian hoopoe (50.00)] in the non-sprayed conventional ones, but no species were found as typical and characteristic of the sprayed conventional olive groves.

Discussion

Yield of olive groves

During our study period (2007) neither extreme climatic conditions nor plant diseases or pests were recorded in the study area, indicating a favorable year for the olive production. The conventional olive groves gave slightly higher, but not significant, mean yield in comparison with the certified organic ones, concerning both the olive oil and the edible olive production (kg tree^{-1}). This differentiation may be due to the systematic use of inputs in conventional olive groves or/and the relatively short period of organic farming practices applied to the rest of the olive groves. Another possible reason may be the proximity of conventional to certified organic olive groves that may have

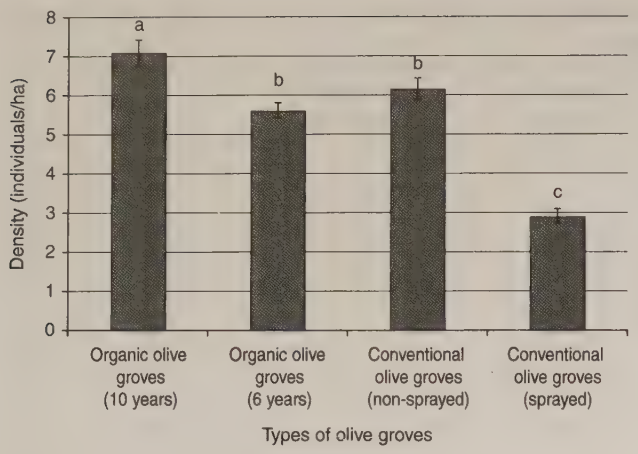

Figure 7. Mean density (individuals/ha) of woody plants in the different types of olive groves (different letters mean statistically significant differences for significance level $P < 0.05$).

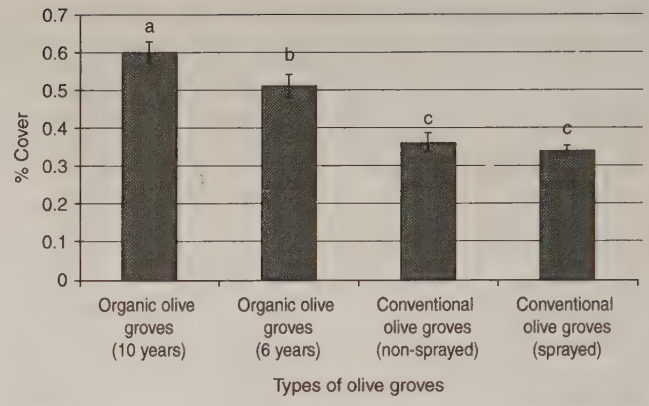

Figure 8. Percentage of woody plant cover (%) in the different types of olive groves (different letters mean statistically significant differences for significance level $P < 0.05$).

delayed the equilibrium between trees and pests and diseases in the organic ones. Parra Lopez and Calatrava Requena[8] stated that organic techniques applied in olive groves of Spain was inversely related to the yield due to a reduction in productivity inherent to organic farming, particularly in the first steps of the conversion process.

Herbaceous plants

The analysis of herbaceous flora of the olive groves studied showed that families Poaceae and Asteraceae exhibited higher proportions in frequency of occurrence. The families Poaceae, Asteraceae, Fabaceae, Caryophyllaceae and Labiatae, among the richest of the Greek flora, were represented in our study by more than 50 taxa each[77,78]. Similar observations have been made by Uysal and Karabacak[79] and Uremis[80] in Turkey and Tzaneli[56] in Greece.

The highest frequency of occurrence (%) was recorded for the species *A. geniculata* in the 6-year certified organic olive groves, a species frequently occurring in olive groves[81]. The highest alpha diversity was recorded in the 10-year certified organic olive groves. More specifically, they exhibited the highest number (species richness), diversity (Shannon, Simpson and Berger–Parker index) and evenness (Evenness index). Based on alpha diversity values there is an indication that 10 years of organic process in olive groves is a significant period for the creation of favorite conditions for the establishment of relatively rich herbaceous plant diversity. Similar results have been reported by a number of other studies conducted in various types of agroecosystems. Also, the species diversity, the total and mean numbers of species are usually higher in organic than in conventional farming systems[82,83]. Pleasant and Schlater[84] also reported that the organic fertilization can increase the diversity of weed species by introducing additional species. Moreover, the abundance of herbaceous species has been found to be higher in certified organic fields than in conventional fields in 16 out of 17 studies reported by Hole et al.[10] in a relevant literature review.

On the basis of the Jaccard index and Sorensen index of similarity (beta diversity) the 10-year certified organic olive groves and the 6-year certified organic olive groves showed the highest values of similarity among all olive grove types as regards the plant diversity of understorey. Obviously, the similar management practices applied and the possible similarity in soil composition were responsible for this result. Conclusively, organic farming practices have resulted in a more diverse herbaceous layer in the olive groves of our study area. Although this is a general conclusion, in similar studies Hald[85] and Hyvönen et al.[12] found high similarity in the herbaceous plant community among organic and conventional fields.

Biomass is a basic characteristic of vegetation, which reflects the fertility of soil resources used by specific plant species[86]. Among all the olive groves managed in different ways a significantly higher amount of herbaceous plant biomass ($g\,m^{-2}$) was produced in the 10-year certified organic olive groves. It is supposed that the non-use of agrochemicals might have a positive effect on biomass production in certified organic olive groves, where the soil after 10 years of organic farming may have been differentiated to a large extent in comparison to the conventional system, but even the inorganic olive groves with shorter period of integration (6 years). The time that is necessary for radical changes to appear in the soil parameters varies greatly. In some cases a few years of organic farming are enough for the appearance of this differentiation[87], while in other cases even a 10-year period of organic agriculture is not sufficient[88]. According to various studies on organic agriculture, a higher density and biomass of herbaceous plants has been estimated in comparison with those found in conventional agriculture[89–91]. In contrast to this, Poveda et al.[92] found that plant biomass of conventional farms exceeded that of certified organic ones, presumably became of the higher nutrient input in the conventional farming system.

Table 9. Summary results of the axes of PCA for selected variables of woody plants.

	Initial eigenvalues		
Component	**Total**	**% of variance**	**Cumulative %**
1	2.874	57.489	57.489
2	0.904	18.074	75.563
3	0.857	17.143	92.707
4	0.346	6.920	99.627
5	0.019	0.373	100.000

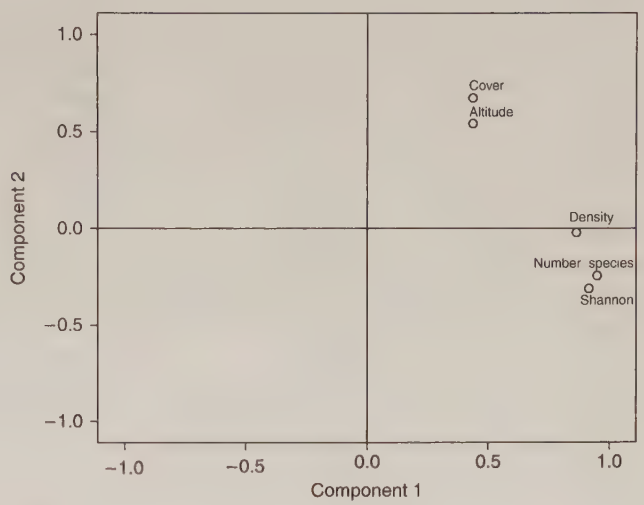

Figure 9. Relationships among selected variables of woody plant species tested with PCA.

Furthermore, positive correlations were found between the following pairs: number of species of herbaceous plants and Shannon diversity index, Shannon diversity index and biomass, number of species of herbaceous plants and biomass, number of species of herbaceous plants and altitude, biomass and altitude, and the Shannon diversity index and altitude. Kharkwal et al.[93] have pointed out that altitude and climatic variables are determinants of species richness. The diversity of life forms usually decreases with the increase in altitude and only one or two life forms remain at extreme altitudes[94]. Also, many studies[95–99] have shown that the relationships between plant species diversity and productivity are strongly scale dependent. Furthermore, at an individual species level, all relationships between plant diversity and above-ground biomass from local scale to landscape and regional scales are positive and non-linear[100]. Vujnovic et al.[101] considered altitude, aspect and slope as important factors in configuration of biodiversity, in contrast to Hashemi[102], considering altitude as a non-meaningful parameter for biodiversity.

Woody plants

The wild-type olive tree (*O. europaea* var. *sylvestris*) as expected, was the most frequently (%) appearing woody plant species, more specifically in the 10-year certified organic olive groves. The species is abundant through the Mediterranean region[81]. Some parameters, such as seed abundance, seed dispersal, possible soil fertility due to organic matter deposition and adaptability to poor soil conditions and dry and hot climate, have favored the dense development of the species, especially in the certified organic olive groves. This is the reason for the use of the wild olive tree as a source of cultivated varieties[103].

Species richness is a simple and easily interpretable indicator of biological diversity[104]. In the present study, the highest value of the woody species richness were estimated in the sprayed conventional olive groves, justified by the fact that herbicides applied in this type of olive groves had no effect on the woody species. The highest values of Shannon diversity index, Simpson index, Evenness and Berger–Parker index were observed in the 6-year certified organic olive groves. According to Petersen et al.[105] flora abundance, richness and diversity indexes were higher in certified organic farms than in conventional ones. Positive effects of organic farming on the flora and fauna diversity have been well documented for various crops[36,106].

On the basis of the Jaccard index and Sorensen index (beta diversity) for the woody plants, the 10-year and 6-year certified organic olive groves showed the highest values of similarity. This differentiation could be attributed to the farming methods applied to the certified organic olive groves being quite different to those applied to the conventional ones.

In our study, an increased woody plant cover (%) and density (individuals/ha) were observed in the 10-year certified organic olive groves. This may be due, in addition to the farming practices applied, to the soil conditions configured under this system. There is scientific evidence that organic farming can improve soil physical and biological properties related to the build-up of organic matter[107,108]. Possibly, the manure applied to the 10-year certified organic olive groves favored the growth of the foliage of woody species resulting in increased cover and density.

According to PCA, a positive correlation between the species number, density and Shannon diversity index of woody plants was recorded. Also, a correlation between percentage of woody plant cover and altitude was detected. Diversity has been recognized as a community attribute related to stability, productivity and trophic structure[109–111]. Species richness or the number of species is currently the most widely used diversity measure. Relative species abundance of a community is another factor that affects diversity[112]. Alatalo[113], Schluter and Ricklefs[114] and Huston[115] have long argued that species abundance and proportional diversity are simply and directly related to the species richness.

Breeding bird species

Our results indicated that the ornithological importance of the study area, independently of the different farming

Table 10. Frequency of occurrence (%) of breeding bird species in olive groves under different management systems.

Species										
Latin name	**Common name**	**2009/147 Annexes**	**SPEC Category[1]**	**Food Category[2]**	**Organic (10 years)**	**Organic (6 years)**	**Conventional (sprayed)**	**Conventional (non-sprayed)**	***F***	***P***
Carduelis cannabina	Common linnet		2	G	–	–	1.7	1.7	0.67	0.56
Carduelis carduelis	European goldfinch			G	11.7	16.7	11.7	5.2	1.29	0.27
Carduelis chloris	European greenfinch			G	1.7	1.7	5.0	5.2	0.70	0.54
Cuculus canorus	Common cuckoo			I	–	1.7	–	–	0.98	0.39
Emberiza cirlus	Cirl bunting			G	6.7	11.7	8.3	3.4	0.98	0.40
Emberiza melanocephala	Black-headed bunting		2	G	21.7	26.7	25.0	31.0	0.45	0.71
Ficedula hypoleuca	Pied flycatcher			I	–	–	1.7	1.7	0.67	0.56
Fringilla coelebs	Common chaffinch			G	33.3	35.0	30.0	31.0	0.13	0.93
Garrulus glandarius	Eurasian jay			I/G	1.7	–	–	–	0.98	0.39
Hippolais pallida	Eastern olivaceous warbler		3	I	35.0	41.7	38.3	41.4	0.24	0.86
H. olivetorum	Olive-tree warbler	I		I	8.3	8.3	28.3	37.9	8.70	0.00
L. collurio	Red-backed shrike	I	3	I	1.7	3.3	–	–	1.23	0.29
Lanius senator	Woodchat shrike		2	I	6.7	5.0	8.3	6.9	0.17	0.91
Muscicapa striata	Spotted flycatcher		3	I	–	1.7	1.7	1.7	0.33	0.79
Oenanthe oenanthe	Northern wheatear		3	I	1.7	1.7	–	–	0.65	0.58
Parus lugubris	Sombre tit			I/G	13.3	10.0	5.0	5.2	1.26	0.28
Parus major	Great tit			I	30.0	40.0	30.0	31.0	0.63	0.59
Passer domesticus	House sparrow		3	I/G	3.3	5.0	3.3	1.7	0.32	0.81
Saxicola rubetra	Whinchat			I	1.7	–	1.7	1.7	0.67	0.57
Steptopelia turtur	European turtle dove	II/2	3	I	8.3	3.3	5.0	3.4	0.67	0.57
Sylvia hortensis	Orphean warbler		3	I	3.3	8.3	–	–	3.32	0.02
Sylvia melanocephala	Sardinian warbler			I	18.3	26.7	11.7	8.6	2.82	0.03
T. merula	Common blackbird	II/2		I	3.3	–	5.0	5.2	1.05	0.37
Upupa epops	Eurasian hoopoe		3	I	–	–	1.7	1.7	0.67	0.56

[1] 'SPEC 1' Species of global conservation concern, i.e., classified as globally threatened. Near threatened or data deficient; 'SPEC 2' for species with unfavorable conservation status in Europe whose global populations are concentrated in Europe; 'SPEC 3' for species with unfavorable conservation status in Europe whose global populations are not concentrated in Europe; 'SPEC 4' for species with a favorable conservation status in Europe whose global populations are concentrated in Europe.

[2] I, insectivorous; G, granivorous; I/G, insectivorous/granivorous.

Table 11. Values of alpha diversity indexes of the breeding bird species in olive groves under different management systems.

	Organic (10 years)	Organic (6 years)	Conventional (non-sprayed)	Conventional (sprayed)	*F*	*P*
Species richness	19a	18a	19a	19a	0.78	0.50
Shannon–Wiener	0.17a	0.21a	0.18a	0.18a	0.85	0.46
Simpson	0.17a	0.20a	0.17a	0.17a	0.91	0.43
Evenness	0.18a	0.21a	0.18a	0.18a	0.83	0.47
Berger–Parker	0.14a	0.19a	0.14a	0.18a	0.34	0.79

Different letters (row) mean statistically significant differences for significance level $P < 0.05$.

Table 12. Values of beta diversity indexes of breeding bird species in olive groves under different management systems.

	C_j*	C_s**
Organic (10 years)–organic (6 years)	0.76b***	0.86b
Organic (10 years)–conventional (non-sprayed)	0.60c	0.75c
Organic (10 years)–conventional (sprayed)	0.58c	0.73c
Organic (6 years)–conventional (non-sprayed)	0.60c	0.75c
Organic (6 years)–conventional (sprayed)	0.60c	0.75c
Conventional (non-sprayed)–conventional (sprayed)	1a	1a

* C_j, Jaccard index; ** C_s, Sorenson index; *** different letters (column) mean statistically significant differences for significance level $P < 0.05$.

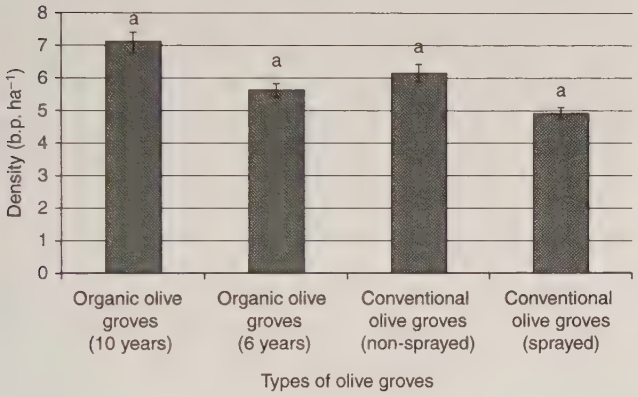

Figure 10. Mean breeding bird density (b.p. ha^{-1}) in the different types of olive groves (different letters mean statistically significant differences for significance level $P < 0.05$).

practices applied to olive groves, seemed to be high. The Eastern olivaceous warbler was the most frequently observed bird species, with the highest percentage of occurrence (%) in the 6-year certified organic olive groves. The species is common in the olive groves, breeding in dry scrub areas, shrub parks, uncultivated land, riverine zones and orchards[116].

It is remarkable that almost the same number of breeding bird species was found in all types of olive groves, whereas the highest values of Shannon, Simpson and Berger–Parker indexes and Evenness diversity were recorded in the 6-year certified organic ones. The highest value of overall breeding bird density (b.p. ha^{-1}) was observed in the 10-year certified organic olive groves. The lack of differentiation in the number of breeding bird species between certified organically and conventionally managed olive groves was possibly due to the relatively short period of conversion to organic system (6 and 10 years for the two organic types, respectively). This period, under the specific environmental conditions, may not be sufficient for the creation of additional niches and subsequent establishment of more numerous species. Although herbicide use in conventional olive groves probably results in decreased foraging opportunities, direct effects on birds appear unlikely to be the main factor determining the number of bird species in this case. Generally, herbicides commonly used in agriculture may not be acutely toxic to birds, but they may have direct harmful effects to some insects that the birds feed upon[117]. However, Round et al.[118] found that mixed fruit orchards were about 75% as rich in bird species as the nearby natural forest. Moreover, in spite of the benefits of certified organic fields to birds, their use by them does not necessarily mean higher reproductive success[119]. Also, the wider the differentiation of vegetation the more species take advantage of the area for their food, reproduction and cover[64].

According to Genghini et al.[34] the differentiation of the avifauna between orchards managed conventionally and organically could be attributed mostly to the different pest management and secondarily to some aspects of environmental differentiation (height, density, cover of trees and increased presence of hedgerows and woodlots). Also, Weibull et al.[120] stated that the main factor affecting bird communities is the supply of insects, the density of which is probably reduced in conventional farms due to chemical treatments. Moreover, effects of herbicides on weed seed resources are suspected to have contributed to the decline

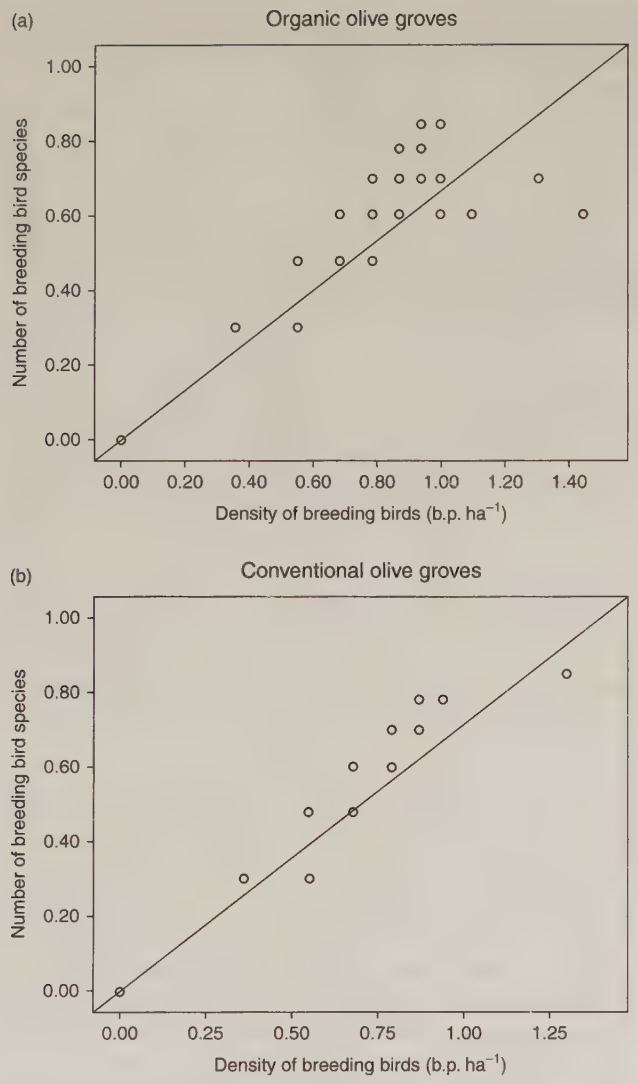

Figure 11. Correlation between the number and density of breeding birds (b.p. ha^{-1}) in a) organic and b) conventional olive groves.

of seed-eating birds. Although effects on winter densities have been shown,[121] population level effects are yet to be demonstrated, partly because of analytical difficulties[122]. However, Wolnicki et al.[123] found that insectivorous and granivorous birds were more abundant on the organic farms, where their mean density was at least twice as high as that of conventional farms. The most likely reason that our certified organically managed fields support richer bird communities is the better foraging opportunities associated with vegetation diversity.

Concerning the presence of species with unfavorable conservation status (SPEC 2 and SPEC 3 species), no clear differentiation among the specific olive grove types was observed. This could be attributed to the selection by these species of a wider habitat rather than a specific olive orchard treated in organic or conventional way.

The reduced density of breeding birds in the conventional olive groves in comparison with the certified organic ones may be due to the increased use of pesticides which lead to the decrease of food (insects, seeds). Herbicide use in conventionally managed fields, which removes broad-leaved herbaceous plants, is listed as a cause of population decline of some farmland birds in Europe[124].

As regards the bird diversity, on the basis of the Jaccard index and Sorensen index (beta diversity), the sprayed conventional olive groves and the non-sprayed conventional ones exhibited the highest value of similarity. Determinants of beta diversity include dispersal and niche limitation[125,126]. Stais and Pyrovetsi[127] reported that structure of vegetation, human activities, abundance of food and weather conditions can affect the spatial distribution and diversity of bird species.

Indicators of bird species richness

The density of breeding bird species (b.p. ha^{-1}) was correlated significantly with the goal parameter 'number of breeding bird species' in our study, being proved as an indicator of the density. Species richness and density of animals can be affected by numerous environmental factors such as habitat, soil type and weather[128]. Nilson[129] in Sweden, Stirling and Wilsey[130] in Chicago, USA, Verhulst et al.[131] in Hungary and Ding et al.[132] in Taiwan found in their studies that bird species richness was correlated with bird density. Also, Kissling et al.[133] suggested that bird and woody plant species richness are linked via functional relationships. In contrast, Ranjit Daniels et al.[134] found that bird species richness was inversely related to woody plant species diversity. However, from similar studies poor relationships between taxa have been reported from groups believed to be good indicators[135–137].

Typical species

The characterization of nine species, occurring almost exclusively in specific farming systems and with high abundances, as typical species of those farming systems, can serve as a conservation tool for the management and monitoring of the study area. Two of them (Eurasian jay, Northern wheatear) were considered as 10-year certified organic olive grove indicators, three species (Common cuckoo, Orphean warbler and Red-backed shrike) as indicators of the 6-year certified organic olive groves and four others (Common linnet, Pied flycatcher, Whinchat and Eurasian hoopoe) as indicators of the non-sprayed conventional olive groves.

The species Eurasian jay, Common cuckoo, Orphean warbler, Pied flycatcher, Whinchat and Eurasian hoopoe prefer as habitat woodlands, orchards, olive groves and cultivations and the species Red-backed shrike, Common linnet and Northern wheatear, prefer shrubs, pastures and firewoods[116,138].

Conclusions

In our study area, the yield (edible olives and olive oil) of the certified organic olive groves was not significantly

Table 13. Number of breeding bird species (y) as a function of seven potential indicators.

Indicator (x)	Management	d.f.	R^2	Sig.	Regression equation
Density of all breeding birds	Organic	1	0.71	0.00	$R = 0.57x + 0.11$
	Conventional	1	0.93	0.00	$R = 0.78x + 0.01$
Number of herbaceous plant species	Organic	1	0.00	0.95	$R = -0.00x + 0.48$
	Conventional	1	0.00	0.30	$R = 0.16x + 0.39$
Biomass production of herbaceous plant species	Organic	1	0.00	0.59	$R = -0.02x + 0.04$
	Conventional	1	0.00	0.36	$R = -0.04x + 0.51$
Number of woody plant species	Organic	1	0.00	0.61	$R = 0.07x + 0.04$
	Conventional	1	0.01	0.20	$R = -0.19x + 0.56$
Density of all woody plants	Organic	1	0.00	0.58	$R = -0.00x + 0.51$
	Conventional	1			$R = 5.33x - 0.78$
Percentage cover of woody plant species	Organic	1	0.00	0.31	$R = 0.07x + 0.44$
	Conventional	1	0.02	0.11	$R = -0.20x + 0.14$
Altitude	Organic	1	0.02	0.08	$R = -1.00x + 0.66$
	Conventional	1	0.06	0.00	$R = -0.17x + 0.76$

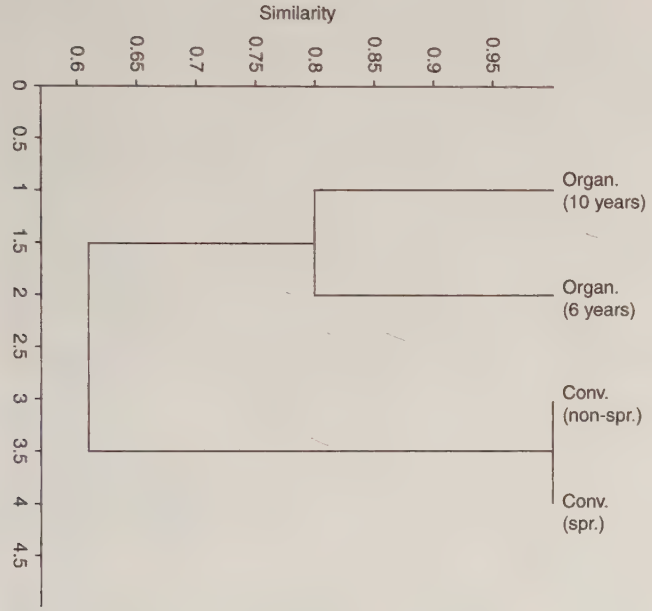

Figure 12. Hierarchical clustering of the bird records in the sampling sites produced by Ward's method in relation to the different farming systems.

Table 14. Results of the IndVal analysis for bird species. Typical species (IndVal > 50%) underlined.

Species	IndVal (%)	Class[1]
Common linnet	50.00	3
European goldfinch	40.54	2
European greenfinch	37.50	3
Common cuckoo	100.00	2
Cirl bunting	41.67	2
Black headed bunting	26.09	1
Pied flycatcher	50.00	3
Common chaffinch	30.61	2
Eurasian jay	100.00	1
Eastern olivaceous warbler	28.43	2
Olive-tree warbler	47.54	4
Red-backed shrike	75.00	2
Woodchat shrike	31.58	3
Spotted flycatcher	33.33	2
Northern wheatear	50.00	1
Sombre tit	36.00	1
Great tit	27.12	2
House sparrow	48.33	2
Whinchat	50.00	3
European turtle dove	46.15	1
Orphean warbler	75.00	2
Sardinian warbler	38.30	2
Common blackbird	37.50	3
Eurasian hoopoe	50.00	3

[1] 1, Organic olive groves (10 years); 2, organic olive groves (6 years); 3, conventional olive groves (non-sprayed). 4, conventional olive groves (sprayed).

different from that of the conventional ones. In the whole study area, 56 species of herbaceous plants belonging to 20 families were recorded. Significant differences in alpha diversity of the herbaceous plants among the different farming treatments were found, with the highest values recorded in the 10-year certified organic olive grove system. Moreover, the highest herbaceous plant diversity expressed by the Jaccard index and Sorensen index was found in both types of certified organic olive groves (10- and 6-years). The highest biomass production of the herbaceous layer was measured in the 10-year certified organic olive groves.

In total, 17 species of woody plants were recorded in our study area. Similarly, significant differences in alpha diversity among the different farming systems were found, with conventional olive groves (sprayed) and 6-year certified organic olive grove systems exhibiting the highest values. However, concerning the Jaccard index and Sorensen index, their highest values were calculated in both types of certified organic olive groves. The highest density and cover of woody plants were observed in the 10-year certified organic olive groves.

In the olive groves studied, 24 species of breeding birds were recorded (15 insectivorous, six granivorous and three insectivorous/granivorous species). Four of them are species of conservation concern according to the EU Birds Directive (2009/147). More specifically, the Olive-tree warbler and Red-backed shrike are included in Annex I, and European turtle dove and Common blackbird in the Annex II/2, of the Directive. No significant differences in bird diversity were found among the different types of olive groves based on the Berger–Parker dominance index, the species richness, Shannon diversity index, Simpson index and Evenness index. However, according to Jaccard and Sorensen indexes, conventional olive groves (sprayed and non-sprayed) showed the highest values. Moreover, no significant differences in the breeding density among the different types of farming systems were recorded. It is important that the density of all breeding birds within certified organic and conventional olive groves proved a good indicator of species richness of breeding birds.

Four species of birds, Eurasian jay, Common cuckoo, Orphean warbler and Red-backed shrike, were strongly associated with a specific farming system. Eurasian jay and Common cuckoo–Orphean warbler–Red-backed shrike were associated with 10-year certified organic olive groves and 6-year certified organic ones, respectively, and could be regarded as 'characteristic' species for the two farming systems.

Consequently, according to our findings there is a trend for increasing alpha diversity of herbaceous plant species in the 10-year certified organic olive groves and beta diversity in the 10- and 6-year certified organic olive groves. Similar trends were detected for alpha diversity of woody plants in the 6-year certified organic olive groves, beta diversity in both types of organic farming, density and cover of woody plants and density of breeding birds in the certified organic olive groves. It seems that the effect of time since the integration of the organic farming procedure was very important for defining the benefits for the herbaceous and woody plants.

We finally conclude that, given the restrictions of our study area (relative small field size, proximity of certified organic and conventional olive groves, short period of organic farming procedure), organic farming favors some aspects of diversity of herbaceous and woody plants of olive grove ecosystems. On the contrary, similar effects on breeding bird diversity and density were not clearly documented. However, breeding bird density proved a good indicator of their richness. Therefore, more comparative research on herbaceous and woody plant species diversity and abundance, as well as on bird and other faunal diversity and abundance, in certified organic and conventional olive groves is needed. Such research has to be based on large-sized farms or, better, on extended areas of uniform management, aiming at the extermination of any possible effects of neighboring farms. Other components of olive grove biodiversity (insects, small mammals, reptiles and soil fauna) must also receive emphasis. Finally, the research should be extended to more biotic and abiotic parameters serving as potential indicators for bird species richness within certified organic and conventional olive groves.

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Renewable Agriculture and Food Systems: 26(4); 317–327 doi:10.1017/S1742170511000135

Diverse perennial crop mixtures sustain higher productivity over time based on ecological complementarity

Valentín D. Picasso[1]*, E. Charles Brummer[2], Matt Liebman[3], Philip M. Dixon[4] and Brian J. Wilsey[5]

[1]Departamento de Producción Animal y Pasturas, Facultad de Agronomía, Universidad de la República, Garzón 780, Montevideo 12900, Uruguay.
[2]The Samuel Roberts Noble Foundation, 2510 Sam Noble Parkway, Ardmore, OK 73401, USA.
[3]Department of Agronomy, Iowa State University, Ames, IA 50011, USA.
[4]Department of Statistics, Iowa State University, Ames, IA 50011, USA.
[5]Department of Ecology, Organismal and Evolutionary Biology, Iowa State University, Ames, IA 50011, USA.
*Corresponding author: vpicasso@gmail.com

Accepted 28 February 2011; First published online 19 April 2011 **Research Paper**

Abstract

Cropping systems that rely on renewable energy and resources and are based on ecological principles could be more stable and productive into the future than current monoculture systems with serious unintended environmental consequences such as soil erosion and water pollution. In nonagricultural systems, communities with higher species diversity have higher productivity and provide other ecosystem services. However, communities of well-adapted crop species selected for biomass production may respond differently to increasing diversity. Diversity effects may be due to complementarity among species (complementary resource use and facilitative interactions) or positive selection effects (e.g., species with higher productivity dominate the mixture), and these effects may change over time or across environments. Our goal was to identify the ecological mechanisms causing diversity effects in a biodiversity experiment using agriculturally relevant species, and evaluate the implications for the design of sustainable cropping systems. We seeded seven perennial forage species in a replicated field experiment at two locations in Iowa, USA, and evaluated biomass productivity of monocultures and two- to six-species mixtures over 3 years after the establishment year under management systems of contrasting intensity: one or three harvests per year. Productivity increased with seeded species richness in all environments, and the positive relationship did not change over time. Polyculture overyielding was due to complementarity among species in the community rather than to selection effects of individual species. Complementarity increased as a log-linear function of species richness in all environments, and this trend was consistent across years. Legume–grass facilitation may explain much of this complementarity effect. Although individual species with high biomass production had a major effect on productivity of mixtures, the species producing the highest biomass in monoculture changed over the years in most environments. Furthermore, transgressive overyielding was observed and was more prevalent in later years, in some environments. We conclude that choosing a single well-adapted species for maximizing productivity may not be the best alternative over the long term and that high levels of species diversity should be included in the design of productive and ecologically sound agricultural systems.

Key words: monoculture, polyculture, richness, overyielding, transgressive overyielding, legume, grass

Introduction

A growing sector of the agriculture community believes that research should focus on developing systems that 'depend largely on contemporary energy, current sunlight rather than scarce fossil fuels (...) and recognize the overriding importance of ecology and uniqueness of place'[1]. Polyculture systems, in which multiple species are grown in mixture, may reduce dependence on external inputs, economic risk and food insecurity, while protecting natural resources[2]. Perennial herbaceous polycultures are mixtures of perennial grass and forb species grown for

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agricultural purposes (grain, forage or biomass production) that can increase diversity and productivity in agricultural landscapes while reducing soil erosion, especially in lands suitable for low-input systems[3–6]. Because these plant communities are composed of perennial species, understanding their long-term dynamics is critically important for management recommendations.

Ecological studies in non-agricultural systems have shown that plant species and functional diversity can increase biomass productivity compared to monocultures, a phenomenon termed as overyielding, but the mechanisms responsible for these effects are still debated[7,8]. Species-rich communities have a greater diversity of traits (e.g., various rooting depths) and may use resources more completely than monocultures. Positive interactions among species can enhance productivity in diverse communities (e.g., legumes can improve nitrogen availability to other species[8,9]). These mechanisms, collectively referred to as complementarity, provided the initial hypothesis for the positive relationship between diversity and productivity[10]. Overyielding may also occur when highly productive species dominate the community, that is, there is a covariance between the species yield in monoculture and its relative yield in the mixture, an example of the selection effect. Because complementarity and selection have different theoretical and practical implications and both may operate at the same time, it is relevant to distinguish between these effects in biodiversity experiments[10].

A second relevant issue is whether overyielding effects observed in biodiversity experiments are consistent across time and environments. Long-term studies in grasslands have shown a consistent and increasingly positive diversity effect on productivity and stability[11], and experiments conducted at multiple locations have shown, in general, a consistent increase in productivity with diversity across locations[12]. However, experiments may operate at spatial and temporal scales smaller than relevant to fully capture agroecosystem dynamics[13,14].

Individual species may perform differently in alternative environments and/or years, and therefore diversity–productivity relationships may change with species composition in agricultural contexts[15]. Also, because agricultural systems require species and cultivars that involve important breeding efforts, understanding the role of individual species on polyculture productivity is relevant to design future breeding programs. Furthermore, identifying the amount of species diversity required to maximize productivity and desirable ecosystem functions is a timely issue[16]. Of special interest in an agricultural context is the identification of situations promoting transgressive overyielding, that is, when a polyculture yields more than the highest yielding component species in monoculture, a phenomenon not usually found in biodiversity experiments[17].

In the first 2 years of a biodiversity experiment, we found a positive biomass productivity–species richness relationship, but the presence of a single high-yielding species in each environment explained most of this diversity effect [15]. In the first paper we did not attempt to identify the ecological mechanisms causing this relationship. However, with an additional year of data, we attempted to evaluate the productivity–species richness relationship in more detail. Because perennial forage species expend energy during establishment developing roots below ground, a complex community may be expected to be in an establishment phase in the first 1–2 years post-seeding. Thus, the third year of the experiment would represent the first year that all species, especially the warm-season grasses, were fully established, and with the addition of that year's data, changes in community dynamics over time could be detected. Therefore, in this paper, we extend the results from our previous paper by analyzing the results of 3 years of our experiment, with the goal of identifying in detail the ecological mechanisms that sustained higher biomass yields over a longer term and evaluating the implications for the design of sustainable cropping systems. We specifically test the following hypotheses: (1) that a positive productivity–species richness relationship was consistent across environments over 3 years; (2) that the identity of the highest yielding species changed over time in 3 years; (3) that a positive overyielding–species richness relationship was due to complementarity among species and not to a selection effect; (4) that complementarity increased as a function of species richness across environments and years; and (5) transgressive overyielding increased over time across environments.

Materials and Methods

Experimental design

Forty-eight plant community entries (i.e., treatments) were assembled using seven perennial species from three taxonomic groups: legumes [alfalfa (*Medicago sativa* L.), white clover (*Trifolium repens* L.), Illinois bundleflower (*Desmanthus illinoensis* (Michx.) MacM. ex B.L. Robins. & Fern.)]; C_3 grasses [orchardgrass (*Dactylis glomerata* L.) and intermediate wheatgrass (*Thinopyrum intermedium* (Host) Barkworth & D.R. Dewey)]; and C_4 grasses [switchgrass (*Panicum virgatum* L.) and eastern gamagrass (*Tripsacum dactyloides* (L.) L.)]. Monocultures of each species were included (7 entries), as well as selected polycultures of two (19 entries), three (13 entries), four (6 entries) and six (3 entries) species (for the list of entries see Picasso et al.[15]). The suite of treatments was not random but systematic so that for most levels of species richness some entries included each individual species and other entries did not. This design allowed us to analyze the effect of individual species on the richness–productivity relationship. Because legumes have been shown to have a major impact on the results of biodiversity experiments[18,19], we included at least one legume in all entries except for monocultures and two-species combinations of grasses, and the same grass species and mixtures were included with each of the three legumes. Monoculture seed

identity and seed density were: alfalfa (cv. 54H51) 838 pure live seeds (PLS) m^{-2}, white clover (cv. Alice) 795 PLS m^{-2}, bundleflower (University of Minnesota accessions) 199 PLS m^{-2}, orchardgrass (cv. Duke) 1625 PLS m^{-2}, intermediate wheatgrass (cv. Oahe) 239 PLS m^{-2}. switchgrass (cv. Cave-in-Rock), 621 PLS m^{-2}, and eastern gamagrass (cv. PMK-24) 15 PLS m^{-2} based on standard agronomic recommendations for Iowa[20,21]. A replacement design was used[22], such that seed density for species in polycultures was reduced proportionally according to the number of species (e.g., a two-species mix included half of the seeds of each monoculture). Thus, the expected proportion of each species in the polyculture was 0.50, 0.33, 0.25 and 0.17 for two, three, four and six species, respectively, and expected evenness was 1 for all polycultures.

Each entry was replicated three times in an alpha lattice design at two locations: the Iowa State University Agronomy and Agricultural Engineering Research Farm in Boone, Boone Co., IA, USA, with a Nicollet loam soil (fine-loamy, mixed, superactive, mesic Aquic Hapludolls) and the ISU Hinds Research Farm in Ames, Story Co., IA, USA with a Spillville loam soil (fine-loamy, mixed, superactive, mesic Cumulic Hapludolls). In spring 2003, plots were tilled before drilling seeds into 4-m × 3-m plots consisting of 20 rows spaced 0.15 m apart. Plots were mowed in June and September 2003 to a 0.15-m height to control weeds. In October 2003, the number of plants of each species present along a 1-m transect per plot was counted. Eastern gamagrass was reseeded by hand in April 2004, because no plants were found in 2003. More details on site characteristics and management practices can be found elsewhere[15].

In 2004, each plot was split into half to form two 2 m × 3 m subplots that were allocated to either a multiple harvest system with removal of all biomass, or to a single-harvest management simulating a perennial grain system with only seed biomass of selected species being removed. The same allocations were used in 2005 and 2006 as well. Plots were machine clipped with a flail-type harvester (Carter Manufacturing, Brookston, IN, USA) equipped with an electronic weigh system. A single 1-m-wide × 3-m-long strip was harvested for biomass through the center of each subplot. The adjacent 50-cm strips on either side of the measured area were cut immediately after data collection so that all biomass was clipped to ground level. Dry matter percentage of samples taken from each subplot immediately before each harvest was used to calculate dry biomass weight per subplot (hereafter referred as total biomass).

In the multiple harvest system, subplots were harvested three times per year in 2004 and 2005, in late-May, mid-July and mid-September; and twice in 2006, in late-June and mid-August. At Ames in 2004 the third harvest was incomplete because of field labor constrains, and so these harvest data were dropped from the analysis. In the single-harvest management, total accumulated biomass of the subplots was harvested in late-October to early November depending on the year. Before that, reproductive structures of four species (Illinois bundleflower, orchardgrass, intermediate wheatgrass and switchgrass) were hand harvested from the entire subplot area as each species matured, weighed and added to the total subplot biomass in 2004 and 2005, but no seed harvest was conducted in 2006.

Two different methods were used to estimate relative abundance of each species (both seeded and weeds). In 2004 and 2005, individual species biomass was measured by clipping two 0.09-m^2 quadrats per plot, sorting species in the laboratory, and weighing them. In 2005 and 2006, individual species ground cover percentage was recorded from visual observations on each plot by the same observer, using a 1 m^2 quadrat located in the center of the plot. Linear regressions for the relative abundance of each species based on biomass and ground cover for 2005 revealed a strong association between the two variables (all $P < 0.0001$ and average $R^2 = 0.78$) for most seeded species with the exception of species with low yields in certain environments (eastern gamagrass in B1 and B3, white clover in A1, wheatgrass in A3), although linear coefficients were not equal to one for several species. Therefore, relative abundance in 2006 was estimated using relative cover data for 2006 and regression coefficients from 2005. We estimated the biomass using the regression coefficients, rather than using the cover estimates, because the linear coefficients differed among species due to density differences, that is, biomass per unit of cover varied among species.

Data analyses

We found location and management system × entry interactions (with crossover), and so all analyses were conducted separately for location and management combinations, hereafter referred to as environments: Boone-one harvest (B1), Boone-three harvests (B3), Ames-one harvest (A1) and Ames-three harvests (A3). The variable of interest was biomass productivity of seeded species, and so biomass of weeds (either spontaneous species or seeded species not intended in a plot) was excluded from the analyses (similar results were obtained when all species were considered, see[15]). For each environment a heterogeneous regression lines mixed model was fit, including richness of seeded species (natural log transformed, continuous variable), year (repeated measures on each plot), richness × year interaction, replications (large complete blocks) and blocks within replication (smaller incomplete blocks of the alpha lattice design). All factors were considered fixed except for replication and block(rep), which were considered random. An autoregressive covariance structure for the residuals was used. In order to fit the correct model, we first tested the hypothesis that the effect of richness was zero for all years by fitting a model with only year and year × richness effects, which we rejected if the year × richness effect was significant. If the first hypothesis was rejected, we tested a second hypothesis of no year × richness interaction by fitting a full model with year, richness and year × richness,

and rejecting it if year × richness was significant[23]. Least-squares means for each entry were calculated, and means were separated using Tukey's multiple comparisons test. Because the presence of individual species was shown to affect the relationship richness–productivity[15], the effect of the single species with higher 3-year average monoculture yields at each environment was tested by conducting regressions for the subsets of plots including and excluding each of these single species for all environments and years.

In order to identify the ecological mechanisms behind the relationships richness–productivity, we partitioned the net richness effect into complementarity and selection effects using the method of Loreau and Hector[10]:

$$\Delta Y = Y_O - Y_E = N\cdot\overline{\Delta RY}\cdot\overline{M} + N\cdot \mathrm{cov}(\Delta RY, M)$$

where the net richness effect ΔY is the difference between the observed yield of the polyculture (Y_O) and the expected yield (Y_E) based on the sum of the component species' monoculture yields weighted by their proportion in the mixture. A positive net richness effect means that the polyculture yields were greater than the average of the monocultures, a condition we define as 'polyculture overyielding'.

The complementary effect is denoted by $N\cdot\overline{\Delta RY}\cdot\overline{M}$, where N is the number of species in the mixture, $\overline{M}$ is the mean monoculture yield of the component species and $\overline{\Delta RY}$ is the mean relative yield deviation across the i species in the polyculture. The relative yield deviation of a given species, ΔRY_i, is the difference of that species' observed relative yield (RY_i)—its polyculture yield divided by its monoculture yield—and its expected relative yield (ERY_i) based on the proportion seeded in the polyculture. A positive value of ΔRY_i means that the species in polyculture yielded more than expected, a condition defined as 'species overyielding'. The selection effect is defined as $N\cdot\mathrm{cov}(\Delta RY, M)$, i.e., the covariance between relative yield deviations and monoculture yields. Positive complementarity effect occurs when the species in the polyculture, on average, yield more than expected based on their monoculture yield and their proportion in the mixture. The selection effect is present if the relative yield deviation is related to monoculture performance. A selection effect is positive when as monocultures yields increase, relative yield deviations in polycultures also increase, and it is negative when as monocultures yields increase, relative yield deviations decrease. Polyculture overyielding, complementarity and selection effects can each be positive or negative independently, and so this method provides a practical framework to understand the mechanisms involved in the richness–productivity relationship. In our calculations, we used the monoculture yields averaged over the three replications in the experiment, and so the mean monoculture yield by environment and year was the basis for comparisons to polyculture yield and relative yield as is recommended for intercropping experiments by Federer[24]. Monoculture yield of eastern gamagrass was zero in 2004 in Boone, and so we excluded it from the analyses for that environment and year to avoid the problem of relative yields approaching infinity when monoculture values are too small[8].

A mixed model similar to the one used for productivity was fit for each of the three effects (i.e., polyculture overyielding, complementarity, and selection) and least squares means by the richness level were calculated across years by environment. The effect of year on the relationship richness–overyielding, richness–complementarity and richness–selection was tested using the heterogeneous regression lines mixed-modeling approach described above.

In order to identify transgressive overyielding we subtracted from each polyculture yield the highest monoculture yield of the species seeded in each mixture. Least-square means for this variable by entry were calculated by environment and year, using a mixed model fitted as described for productivity. Mixtures with means significantly different from zero (at the 10% probability level) were identified as showing transgressive overyielding. The proportion of mixtures showing transgressive overyielding was calculated by environment and year, and differences in this proportion between first and last years were assessed with a Z-test assuming a normal approximation of the binomial distribution.

All analyses of variance and contrasts were performed using PROC MIXED and regression coefficients were calculated using PROC REG, in the SAS statistical software package[25]. Statistical significance was assessed at the 5% level unless otherwise indicated.

Results

Productivity–richness relationship over time

There was a strong linear association between the observed richness of seeded species and the original richness of seeded species at the time of sowing for each combination of environment and year ($P < 0.0001$; data not shown). Analyses of effects of richness on productivity gave similar results for both measures of richness. For clarity and consistency with the complementarity-selection analyses, we show the results here using seeded species richness.

We found an overall effect of species richness on productivity for all environments ($P < 0.0001$). Environments B1 and B3 had no richness × year interaction; therefore, a model without interaction was fit, where productivity was a log-linear function of richness (for B1, $b_1 = 280$; for B3, $b_1 = 478$, all $P < 0.0001$). A richness × year interaction was found in A1 ($P = 0.02$) and A3 ($P = 0.03$), but slopes were positive for all years (for A1: $b_1 = 275$ in 2004, $b_1 = 192$ in 2005 and $b_1 = 331$ in 2006; for A3: $b_1 = 261$ in 2004, $b_1 = 395$ in 2005 and $b_1 = 405$ in 2006, all $P < 0.0001$). There was no consistent trend of either strengthening or weakening of the richness–productivity relationship with years, except for environment A3, where the slope increased over time.

Individual species effects on productivity over time

Biomass yield of monoculture plots differed among species within environments for all years (Fig. 1) except for Ames in 2006. In B1, the highest monoculture yields were from intermediate wheatgrass in 2004, but no significant differences were found among the three highest yielding species in 2005 and 2006. In B3, alfalfa had the highest yields in monoculture every year, and no other species had equivalent yield in any year. In A1 intermediate wheatgrass had the highest monoculture yields in 2004, but no differences were observed among the three highest yielding monocultures in 2005 and 2006. In A3, no significant differences were found among species in any year. Therefore, maximum monoculture yields were consistently observed from a single species in only one environment every year (alfalfa in B3); no single species show a similar pattern in the other environments.

Alfalfa in the multiple harvest management and intermediate wheatgrass in the single-harvest management were the species with highest yields in monoculture in both locations averaged over the 3 years. In A3 and B3, productivity of plots with alfalfa was consistently higher than that in plots without alfalfa across richness levels. In A1 and B1, productivity of plots with intermediate wheatgrass was usually higher than that in plots without intermediate wheatgrass across richness levels.

For the subset of plots excluding the highest-yielding species in each environment, in general productivity increased log-linearly with seeded species richness (Table 1). The only exception was year 2005 for the one harvest management environments (plots without intermediate wheatgrass), where no increase in productivity was found with richness. For the subset of plots including the highest-yielding species in each environment there was a more diverse response of productivity to richness (Table 1 and Fig. 2) across environments. In B3, plots including alfalfa in the seeded mix had constant and high productivity regardless of seeded species richness. In A1 and B1, in 2004 and 2005 productivity of plots including intermediate wheatgrass did not change with richness, but in 2006, productivity did increase with richness. Finally, in A3, the first 2 years productivity increased with species richness and in 2006 there was no change.

Polyculture overyielding, complementarity and selection effects

A positive polyculture overyielding effect was observed across all environments (Figs. 3 and 4). Therefore, polyculture yields were greater than the average of the component species in monoculture. For all environments polyculture overyielding increased as a log-linear function of species richness ($b_1 = 255.3$ in B1, $b_1 = 461.4$ in B3, $b_1 = 219.8$ in A1, $b_1 = 333.1$ in A3, $P < 0.0001$ for all environments).

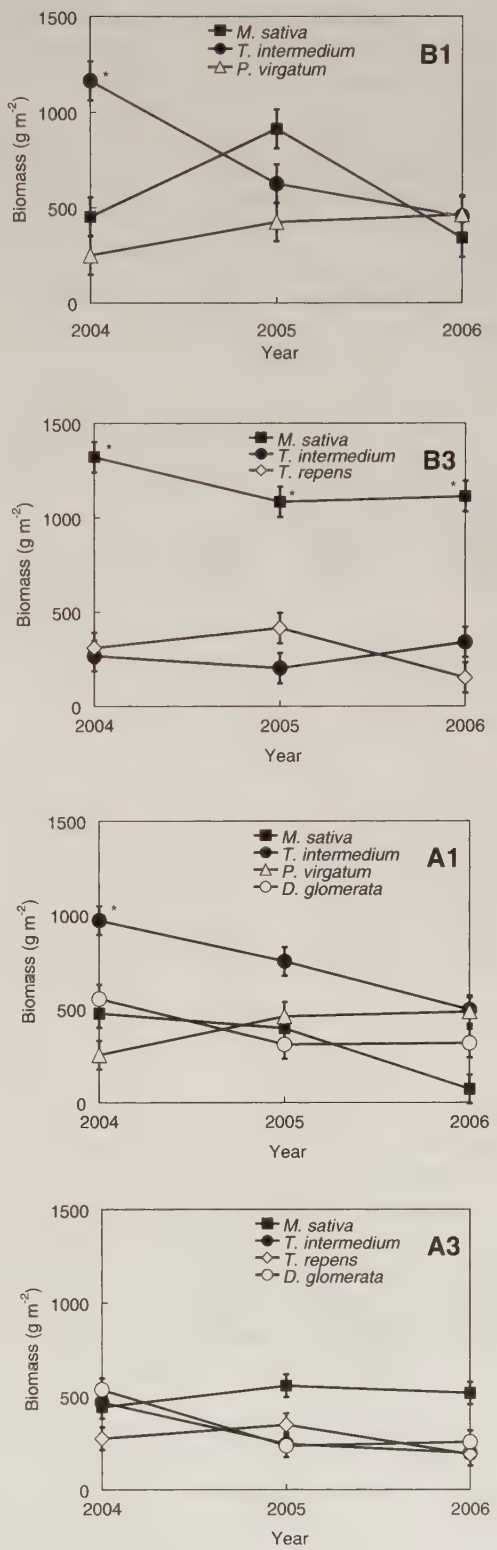

Figure 1. Means of biomass productivity ($g\,m^{-2}$) of the highest-yielding monocultures over the 3 years in each environment (B1: Boone-one harvest; A1: Ames-one harvest; B3: Boone-three harvests; and A3: Ames-three harvests). Species included had either the highest or second to high yield in at least 1 year in each environment. Standard error bars for the mean in each environment are shown. Means marked with * were significantly different from the other means shown below in that year in a Tukey multiple comparisons test at 5%.

Table 1. Linear regression parameters (b_0 and b_1), *P*-values and adjusted R^2 for models of biomass productivity of seeded species ($g\,m^{-2}$) as a function of natural logarithm of seeded species richness in each environment and year, for subsets of plots including (with) and excluding (without) the species with highest monoculture yields averaged over the 3 years in each combination of location and harvest management, referred as environments (B1: Boone-one harvest, A1: Ames-one harvest, B3: Boone-three harvests and A3: Ames-three harvests). The one harvest management includes seed and vegetative biomass harvested at the end of growing season, the three harvest management is the sum of three vegetative biomass cuts throughout the growing season. In the cases that linear regressions are not significant at 5%, the null model is shown (mean).

Environment	Subset of plots	Year	b_0	b_1	*P*-value	Adj. R^2	Mean
Boone-one harvest (B1)	With *T. intermedium*	2004					706
		2005					832
		2006	333	135	0.0311	0.07	
	Without *T. intermedium*	2004	−32	365	<0.0001	0.17	
		2005					535
		2006	165	144	0.0274	0.04	
Boone-three harvests (B3)	With *M. sativa*	2004					1040
		2005					1110
		2006					1052
	Without *M. sativa*	2004	−67	329	<0.0001	0.24	
		2005	−11	241	<0.0001	0.19	
		2006	10	251	<0.0001	0.21	
Ames-one harvest (A1)	With *T. intermedium*	2004					792
		2005					672
		2006	299	197	0.0005	0.20	
	Without *T. intermedium*	2004	149	211	0.0110	0.06	
		2005					299
		2006	42	272	0.0015	0.10	
Ames-three harvests (A3)	With *M. sativa*	2004	361	148	0.0458	0.06	
		2005	475	136	0.0244	0.08	
		2006					640
	Without *M. sativa*	2004	115	196	0.0031	0.08	
		2005	−84	307	<0.0001	0.22	
		2006	−91	277	<0.0001	0.31	

A positive complementarity effect was observed across all environments (Fig. 3), and complementarity increased as a log-linear function of species richness ($b_1 = 447.8$ in B1, $b_1 = 331.9$ in B3, $b_1 = 208.2$ in A1, $b_1 = 223.8$ in A3, $P < 0.0001$ for all environments). This indicated that on average the species in polycultures had relative yields greater than expected based on their seeded proportion (i.e., overyielding of individual species was observed) and that this complementarity effect was greater at higher richness levels.

Selection effects differed among environments (Fig. 3). In B1 selection effects were negative overall, and decreased as negative log-linear function of richness ($b_1 = -215.1$, $P = 0.0011$). In B3 and A1, there were no trends in selection effects with richness ($P = 0.1651$ in B3 and $P = 0.8639$ in A1). In A3, selection effects were mainly zero or positive across species richness levels, and the selection effect increased as a log-linear function of richness ($b_1 = 118.2$, $P = 0.0083$).

The relative yield deviation (ΔRY_i) of orchardgrass ranged from 0.4 to 1.8 and was the largest of all species in polycultures across all richness levels in all environments, indicating that orchardgrass overyielding was highest of all species. Relative yield deviation for alfalfa ranged between 0 and 0.3 across richness levels in all environments. The relative yield deviations for all other species were usually zero across richness levels in all environments.

Although polyculture overyielding was observed throughout the experiment in all environments and years, transgressive overyielding was detected mainly in Ames environments (Fig. 4). The frequency of transgressive overyielding (percent of mixtures sown showing this effect) increased over time, reaching 20% in A1 and 30% in A3 in the last year. Transgressive overyielding was observed in mixtures with all levels of species richness, but was more common in the mixtures with six species sown (up to 67% of these plots in A3-2005 and 2006). Mixtures with 2 years of transgressive overyielding were: alfalfa–orchardgrass, alfalfa–orchardgrass–wheatgrass, clover–orchardgrass–wheatgrass, alfalfa–clover–orchardgrass–wheatgrass, alfalfa–bundleflower–orchardgrass–wheatgrass, alfalfa–bundleflower–orchardgrass–wheatgrass–switchgrass–gamagrass and clover–bundleflower–orchardgrass–wheatgrass–switchgrass–gamagrass. The absolute value of transgressive overyielding (difference between the mixture yield and maximum monoculture yield) ranged from 142 ± 81 to

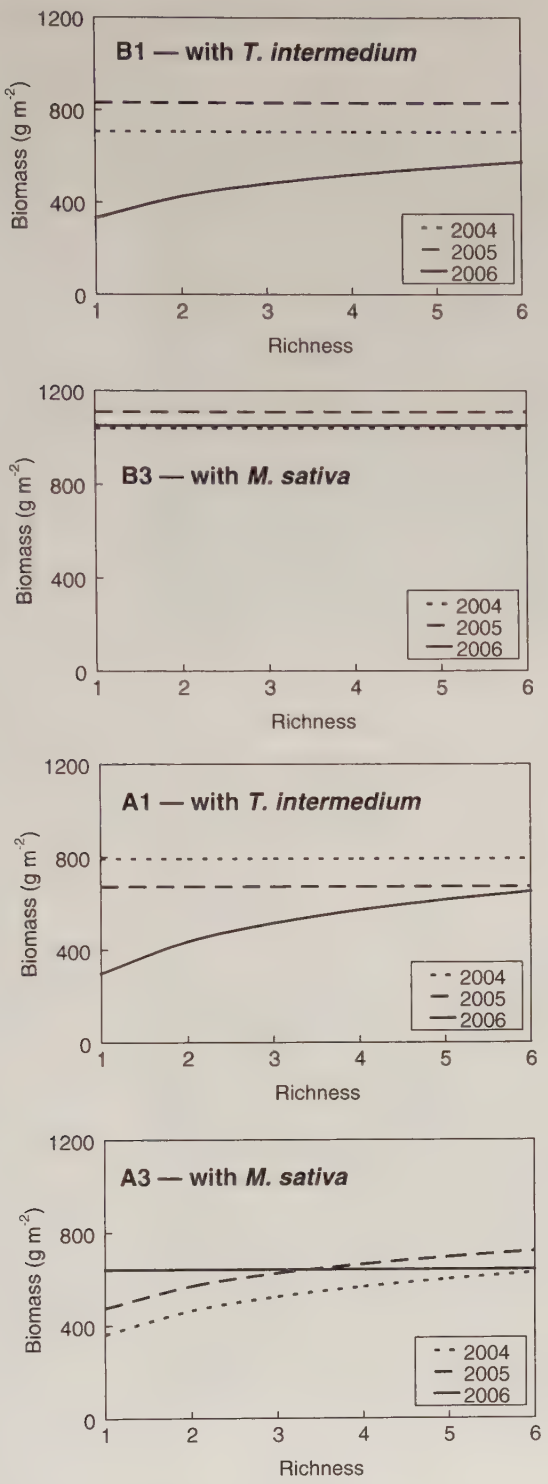

Figure 2. Regression lines for biomass productivity of seeded species ($g\,m^{-2}$) as a function of seeded species richness in each year, for plots including the species with highest 3-year average monoculture yield in each environment (B1: Boone-one harvest; A1: Ames-one harvest; B3: Boone-three harvests; and A3: Ames-three harvests). Regression parameters or means in each case are given in Table 1.

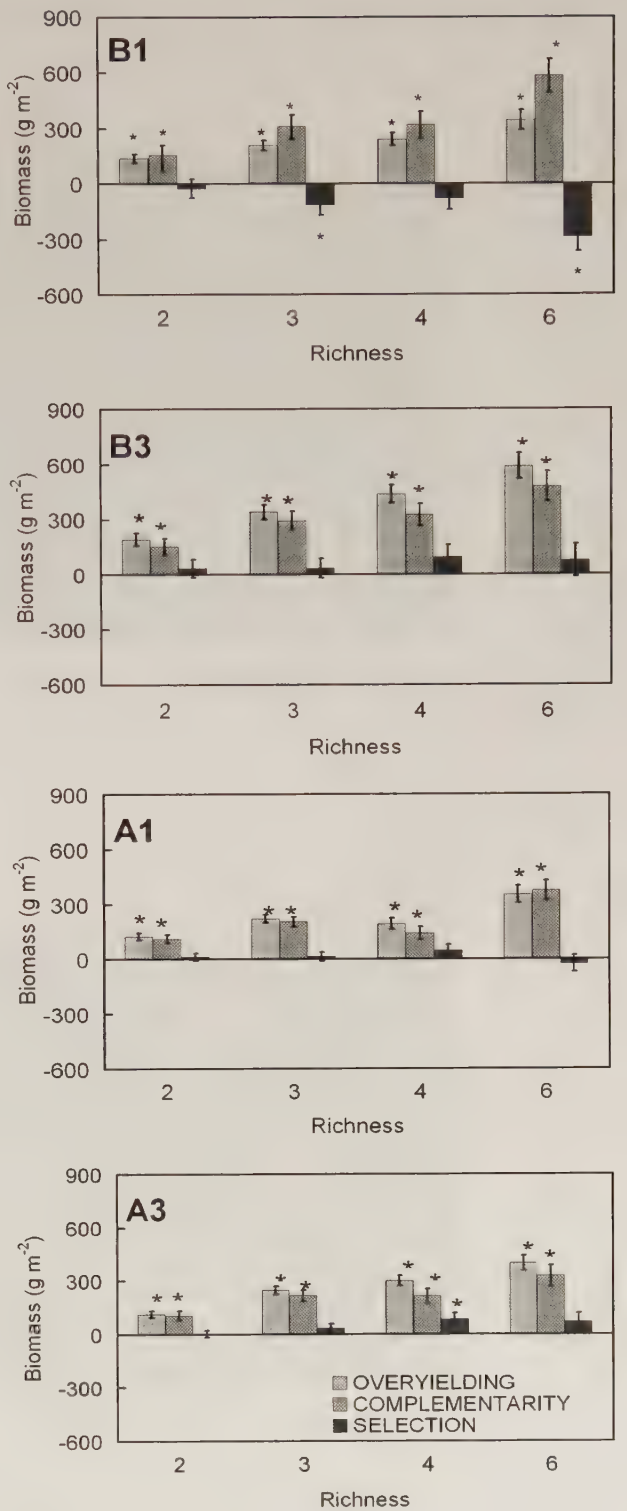

Figure 3. Polyculture overyielding (polyculture yields greater than the average of the monocultures), complementarity (species in polyculture yield more than expected based on their monoculture yield and proportion in the mixture) and selection (species relative yield deviation related to monoculture performance) effect means ($g\,m^{-2}$) by seeded species richness averaged over the 3 years for each environment (B1: Boone-one harvest; A1: Ames-one harvest; B3: Boone-three harvests; and A3: Ames-three harvests). Means marked with * were significantly different from zero at 5%.

$489 \pm 147\,g\,m^{-2}$. It should be noted that in order to detect (statistically) significant differences in our experiment the required yield (agronomical) differences were relatively

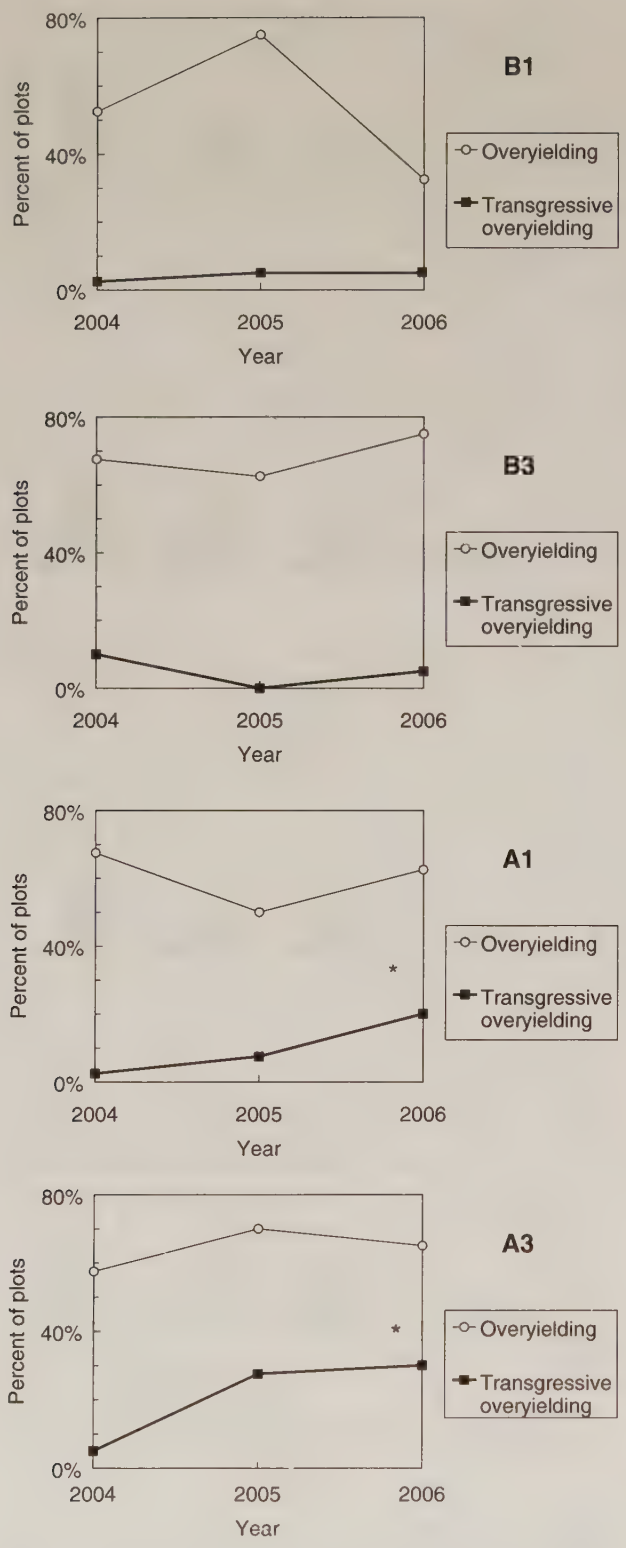

Figure 4. Percent of plots that showed significant polyculture overyielding (polyculture yields greater than the average of the monocultures in the mixture, open circles) and transgressive overyielding (polyculture yields greater than the highest monoculture in the mixture, filled squares) over the 3 years of the experiment in each environment (B1: Boone-one harvest; A1: Ames-one harvest; B3: Boone-three harvests; and A3: Ames-three harvests). Values in 2006 marked with * were significantly different from the values in 2004, at 5%.

high for productive agriculture situations (1420–4890 kg ha^{-1}). In order to find mixtures with greater yield than any monoculture in the experiment, we further identified mixtures that included the highest-yielding species in monoculture in that particular environment and year. When this environment-wise transgressive overyielding was assessed, we found only 5% of plots in A1 and 23% of plots in A3 in the last year.

Discussion

The positive relationship between productivity and seeded species richness did not change over time in our experiment with agronomically relevant species in agricultural conditions. This result provides further evidence that richness effects are not transient, in accord with the results of many ecological studies[17]. Other studies lasting longer than 5 years have found a strengthening of the positive richness–productivity effect, but over the 3 years of our study, we could not detect this effect.

Across all environments and richness levels, the net richness effect was positive; that is, polyculture overyielding was observed. Complementarity effects were positive (Figs. 5 and 6) and selection effects either negative or zero. Complementarity arises when the average relative yield deviation of individual species in the polyculture versus their performance in monoculture is greater than zero. In the absence of a selection effect, the polyculture will exhibit overyielding if complementarity is present. However, complementarity may be counteracted by a negative selection effect, resulting in a polyculture that does not exhibit overyielding. In our experiment, orchardgrass and alfalfa showed species overyielding—i.e., they consistently had ΔRY greater than zero, whereas most other species had ΔRY consistently less than zero. This suggests that orchardgrass and alfalfa were largely responsible for the positive complementarity effect. The largest complementarity effect was the result of orchardgrass overyielding in polycultures with legumes. Although we did not measure plant nitrogen, orchardgrass leaves in polycultures with legumes were visually greener than leaves in monocultures (personal observation). This suggests that nitrogen facilitation may have explained the complementarity effect, consistent with other experiments that measured nitrogen pools (see e.g., Fargione et al.[8]). Positive selection effects are observed when species with high yields in monoculture overyield in polycultures and low-yielding monocultures perform poorly in polycultures. In contrast, negative selection effects exist when species with low yields in monoculture overyield in polycultures and species with high monoculture performance underyield[26,27]. In our experiment, alfalfa generally was highly productive in monoculture and overyielded in mixtures, intermediate wheatgrass was highly productive in A1 but did not overyield in mixtures, and orchardgrass yielded poorly in monocultures but overyielded in mixtures in all environments. As a result of these species interactions, in most

Figure 5. Overview of perennial polyculture plots in Boone, IA, USA in June 2006, before biomass harvest.

Figure 6. Overview of perennial polyculture plots in Ames, IA, USA in May 2005, after the first biomass harvest.

environments no selection effects were observed because the positive effect of alfalfa was canceled out by the negative effect of orchardgrass. In B1, a negative selection effect was observed due to orchardgrass overyielding and alfalfa, with a high monoculture performance, not overyielding substantially in mixtures.

Our results using cultivars of highly productive forage species are consistent with ecological experiments at multiple sites throughout Europe[12] where polycultures overyielded and complementarity effects were positive, but selection effects were variable across sites. Also, long-term experiments on Minnesotan grasslands showed that the complementarity effect increased consistently over time, whereas the selection effect was positive during the first 2 years and negative later[8]. This shift occurred because monoculture yields changed with time as initially low-yielding species became the highest-yielding ones in later years[8]. A negative selection effect has been observed in communities with varying evenness and richness[26] and in polycultures containing a grass [*Arrhenatherum elatius* (L.)

P. Beauv. ex J. Presl et C. Presl] with high monoculture performance that reduced all other species in mixtures[28]. Species that increase overyielding by increasing the relative yields of other highly productive species, due to improving nitrogen availability for instance, can produce a positive selection effect, as observed for *Trifolium pratense* L. and *T. repens* L.[28]. Finally, a recent meta-analysis of plant experiments found that, on average, complementarity increased with time in experiments lasting more than 5 years, while selection effects remained constant[17]. Overyielding and transgressive overyielding (i.e., the polyculture yields more than the highest-yielding monoculture) increased in experiments that ran for longer time frames because complementarity effects among species increased with time. Since most experiments are short term and transgressive overyielding in plant communities may take 5 years to be observed, the potential for transgressive overyielding has likely been underestimated. This also is likely in our experiment.

Several high-diversity polycultures had yields similar to the highest-yielding species in monoculture. Furthermore, in various environments and years, transgressive overyielding was not observed, and plots including the highest yielding species in monoculture did not change their yields with richness. Therefore, in certain environments (e.g., B3) with certain species well adapted to intense management (e.g., alfalfa), monocultures may be the best production option. Results similar to these have been used to argue that monocultures or simple mixtures of two species (bicultures) should be a better and more achievable target for sustainable agriculture systems in the short term[16]. Although we agree that levels of plant diversity comparable to natural ecosystems (>10 species) may not be needed in agricultural systems, 'reasonable' levels of diversity (four to six species) may be of better value. We support this statement based on two of our findings.

First, in most of our environments the species with highest monoculture yields changed over time. Therefore, over the long term, it is not possible to define the 'best' monoculture. Individual species may change their relative productivity because of external factors like climatic variability (rainfall and temperature) or pests and disease pressure over the years, but also because of internal factors related to their life cycle and age of the plant. In our experiment for instance, switchgrass initially had a very low productivity, which increased constantly over time (possibly related to the root growth in the establishment years), whereas intermediate wheatgrass had an opposite behavior (perhaps related to disease pressure). If we additionally consider that management (e.g., harvesting frequency) can (and usually does) change in real farming situations over the years, we find that choosing a single 'best' perennial species that could maximize productivity becomes very difficult.

Second, in several environments and years, transgressive overyielding was observed, and productivity did increase with species richness even in the plots including the highest-yielding species in monoculture. This suggests that diverse polycultures may be more stable over longer time frames than monocultures or bicultures, at least in perennial agriculture systems using low levels of inputs. Although in the short term the best-adapted monocultures may equal or exceed polyculture performance, in the long term, polycultures may be advantageous and transgressive overyielding may become more common.

Finally, in this paper, we focus only on one ecosystem function, i.e., biomass productivity. Sustainable agriculture has multiple goals and, as other authors have suggested, when other ecosystem functions are considered (e.g., pest and weed suppression, soil fertility), the minimum number of species required to maximize all functions may increase[15,29,30].

Conclusion

In summary, as our perennial polyculture communities had more time to establish and grow and a third year of data were measured and analyzed, the positive biomass productivity–species richness relationship remained consistent across time and environments, and this was due to increasing ecological complementarity over time and not selection effects. In some environments, transgressive overyielding started to be detected, and the identity of the highest-yielding species changed over time, which contrasts with our results from the first 2 years. This stresses the need for continuous funding of long-term studies of perennial polyculture communities.

In this experiment, we used commonly grown forage species to examine the ecological mechanisms that explain the relationship between productivity and species richness in mixtures. We intended to relate our results using agriculturally relevant species to previous research using grassland and non-agricultural assemblages of plants. Our results are broadly congruent with the ecological literature, in which positive productivity-richness effects are due to complementarity among species, but not selection effects. We could extrapolate our work based on the ecology literature to suggest that the value of mixtures would increase with time as complementarity effects become more common and transgressive overyielding is more frequent. Therefore, choosing a single well-adapted species for maximizing productivity in a monoculture may not be the best alternative over the long term and reasonably high levels of species diversity (four to six species) should be included in the design of productive and ecologically sound perennial agricultural systems.

Acknowledgements. This research was co-funded by grants from R. Baker Center for Plant Breeding at Iowa State University, Ames, IA, to E.C.B.; Fulbright-Uruguay Graduate Fellowship, NCR-SARE Graduate Student Project GNC05-055, Natural Systems Agriculture Graduate Fellowship from The Land Institute, Salina, KS, and CSIC–UDELAR (Uruguay) to V.D.P. We thank Mark Smith and students in the ISU forage breeding lab for field and lab assistance, the Graduate Program in Sustainable Agriculture at ISU for support and anonymous reviewers for improving the manuscript.

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Renewable Agriculture and Food Systems: 26(4); 328–341 doi:10.1017/S1742170511000123

Urban people as paddy farmers: The Japanese Tanada Ownership System discussed from a European perspective

Pia R. Kieninger[1]*, Eiji Yamaji[2], and Marianne Penker[3]

[1]Institute of Integrative Nature Conservation Research, Department of Integrative Biology and Biodiversity Research, University of Natural Resources and Life Sciences, Vienna, Gregor Mendel Strasse 33, 1180 Vienna, Austria.
[2]Department of International Studies, Division of Environmental Studies, Graduate School of Frontier Sciences, The University of Tokyo, 5-1-5 Kashiwanoha, Kashiwa City 277-8653, Japan.
[3]Institute of Sustainable Economic Development, Department of Economics and Social Sciences, University of Natural Resources and Life Sciences, Vienna, Feistmantelstrasse 4, 1180 Vienna, Austria.
*Corresponding author: pia.kieninger@boku.ac.at

Accepted 28 February 2011; First published online 15 April 2011 **Research Paper**

Abstract

The degradation of the traditional cultural landscape due to abandonment of agricultural management is perceived as a serious problem in different parts of the world. Rising consciousness concerning this issue in Japan led to the formation of numerous voluntary civil farming programs. This paper presents a multi-method case study conducted in Japan (Ōyamasenmaida, Chiba prefecture) about a highly relevant rural–urban cooperation, where landholders lease out their rice terraces to city dwellers to grow their own rice under the intensive instruction and well-organized support by local farmers and other local experts. The activity is known as 'Tanada Ownership' (tanada means rice terrace). It is spread over the country and promises, in contrast to the short-term individualistic European models, long-term rural–urban relations, the valorization of local knowledge and natural resources as well as the maintenance of the rice-terrace landscapes in several regions of Japan. The particular goal of this research is the investigation of the 'how' and 'why' of the system and the motivation of its participants. The Japanese approach is compared with similar European initiatives and conclusions focus on the particularities of the Japanese Ownership System and its transferability to the European context. Despite the innovativeness and popularity of the Ownership System, scientific studies are relatively scarce and none of them published are in English. This article therefore presents an original and important contribution to the scientific community, as it provides insights into the Tanada Ownership System and puts it into an international context by comparing it with European initiatives of voluntary farm work.

Key words: Japan, cultural landscape conservation, Ōyamasenmaida (Chiba Prefecture, Kamogawa City, Japan), Tanada Ownership System, voluntary civic engagement, voluntary farm work

Introduction

Voluntary farm work of the urban population had some tradition in Europe during and after the Second World War. Urban volunteers attended (school) harvest camps, week-end farm clubs and other land-based activities to mitigate food shortages[1,2]. In the following period of surplus food production, such engagements became irrelevant. Recently, not only in Europe but also in other industrialized countries, volunteers and civil society organizations started to support direct involvement with land and farm work again[3,4]. In the USA, the term 'civic agriculture' was created in 1999 by T.A. Lyson to highlight small(er)-scale (family) farms and local-community-based food production activities and associations as counter movement to the US–American industrialized, globalized, large-scale agriculture[5]. Civic agriculture is a very broad 'concept' characterized by local rural–urban networks between consumers and producers striving for an economically, environmentally and socially sustainable agricultural system, including, e.g., organic farming, direct marketing, alternative (agri)-food stores, and/or movements[5]. Also 'urban agriculture', 'community

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gardens' (in Europe 'allotment gardens') or the 'farm to school (FTS) program' can be defined as civic agriculture[6–8]. In contrast to the Japanese Tanada Ownership System presented in this article, urban agriculture and community gardens take place in an urban context and mostly on public land. The FTS program aims at prevention of child obesity by including nutrition in the curriculum and by changes in the school lunch menus toward more fresh food (fruits, vegetables, eggs, honey, meat, etc.) from local farmers[7]. Supporting local farmers helps to revitalize the rural community[7]. In contrast to the systems analyzed in this paper, a direct involvement of teachers and pupils in agricultural activities, beyond farm visits, however, is not common[7,9].

This paper presents a popular, well-established and organized form of direct civic voluntary farm work in the Japanese rice terrace landscapes that are endangered by abandonment of agricultural land use. The results are discussed against literature on voluntary farm work, landscape stewardship and nature conservation in Europe, Australia and the USA. Conclusions regarding the particularities of the Japanese Ownership System and its transferability to the Western context are drawn.

Rice is the traditional main staple food of Japan. Its cultivation has a tradition of more than 2000 years. It can therefore be considered as a fundamental feature of the Japanese cultural landscape, which is a place of high biocultural diversity[10]. Following the Western lifestyle the eating habits of the Japanese people have changed and rice consumption decreased by half from 118.3 kg to an annual per capita consumption of 59 kg between 1962 and 2008[11]. Furthermore, because of a very small average farm size (1.38 ha[12]) and high costs of labor[13], Japanese rice farmers are confronted with up to 10 times higher production prices, compared to foreign producers[14]. From an economical point of view, the cultivation of rice therefore becomes more and more unalluring. Thus, it is not surprising that the number of farm households has decreased by 59% between 1950 and 2008[11,12]. The farmland area diminished by 24% (from 6.09 million hectares in 1961 to 4.63 million hectares in 2008) to 12% of the country's territory[12]. A total of 59% of the agricultural key workers were 65 years or older in 2008[12]. These structural and demographic developments are reflected not only in a continuously dwindling food self-sufficiency rate to the lowest among the major developed countries[15] but also in the loss of biocultural diversity associated with traditional agricultural landscapes.

The traditional cultural landscape of Japan has been shaped by thousand of years of agricultural land use[10]. Because of its long history and the co-evolution of natural and social systems, the landscape is very rich in different habitat types, plant and animal species, customs and culture. The Japanese people perceive it as their 'mother landscape'[16], as some kind of arcadia, they are longing for. Its degradation due to an insufficient level of management is listed in the Fourth National Biodiversity Strategy as one of the main reasons for the loss of biodiversity[17].

In the late 1980s, the first cultural landscape conservation movements were emerging at the local level[18]. Whereas engagement in woodland management is restricted only by few legal rules, there were many legal limitations for civil society participation in agricultural cultivation[18]. With very few exceptions, exclusively farmers were allowed to own and cultivate agricultural land. Non-farmers could just engage in public allotment gardens or to support existing farmers as volunteers[18]. However, some years later a special agricultural leasing partnership program, called 'ōnā seido', was initiated, where non-farmers have the opportunity to rent agricultural land. Ōnā is the 'Japanized' English word for owner, whereas seido means system. Ōnā seido translated into English makes 'Ownership System'. A more correct term, however, would be 'Tenure System', as the participants in the Ownership System, the owners (ōnā), are not owners, but tenants.

The Ownership System can be regarded as an urban–rural coalition, where non-farmers (predominantly city dwellers) engage in farming activities. Against the payment of a participation fee, they rent their own agricultural land, cultivate it and thus contribute to the revitalization of the rural society and preservation of the traditional cultural landscape.

As it is generally prohibited in Japan by agricultural legislation to lease farm land out to non-farmers, until 2003 the leasing out in the Ownership System could only be done indirectly via a city or an agricultural cooperative association[19]. Later, however, a special law came into action, which allows every prefecture and/or city to apply for the designation as a 'special district for policy renovation' ('tokku'). In these tokku districts, the leasing restrictions do not apply and farmers are allowed to lease out their agricultural land directly to non-farmers[19].

Apart from urban participants (tenants), landowners and local supporter groups are further stakeholders in the Ownership Programs. The local supporter groups play a fundamental role because the landowners are often too old for field work, while the mostly inexperienced tenants need guidance. Moreover, tenants participate only in some special occasions a year, as for example, sowing, transplanting rice, weeding or harvesting. All the work in between is carried out by either the landowners or the local supporter groups.

The Ownership System became very popular in Japan and spread throughout the country, in particular the Tanada Ownership System. Tanada is the Japanese word for rice terrace/terraced paddy fields. In most cases, rice terraces are situated in the mountainous regions of Japan, which are most threatened by land abandonment[20]. But as also shown in the study of Swanwick[4], people prefer landscape with diverse landforms to lowlands. So the popularity of Ownership Programs in rice-terrace landscapes may also be explained with their aesthetic beauty[21,22]. Apart from that, they evoke strong feelings of timelessness, identity and links with the past[4].

The first Tanada Ownership System started 1992 in the village Yusuhara (Kochi Prefecture, Japan) in Shikoku

Island[23]. All around Japan 187 Ownership programs were counted in 2008[24].

Compared to the popularity and innovativeness of the Ownership System, scientific studies are relatively scarce[22,25–27]. Besides that, all of them have been published exclusively in Japanese. Thus, there is little knowledge of this movement among non-Japanese scientists. The particular goal and groundbreaking aspect of our research is to investigate the system from a European viewpoint and to provide a new and deep understanding in the Ownership System by the holistic research approach. The Japanese Ownership System is compared with similar European initiatives. Conclusions focus on the particularities of the Japanese Ownership System and its transferability to the European context.

The factors determining the choice of the study site were the acknowledged scenic and ecological value of its cultural landscape and personal contacts with the local population.

Prior to this study, some research was done on vegetation[28], visitor's perception of the scenery of tanada landscapes[29], cultural landscape conservation methods[30] and on the Ownership System itself[26,27].

The questions guiding the present research are of clear exploratory nature:

- Why did landowners and local people found the Ownership System in Ōyamasenmaida?
- How is the Ownership System organized?
- What are the provenance, professional background, age and motivations of the tenants of the Ownership System?
- What are the tenants' attitudes regarding cultural landscapes and different ways of protecting it?

The study area

Ōyamasenmaida is a rice-terrace landscape located in the mountains (Fig. 1), in the south-eastern end of the Boso Peninsula (Chiba Prefecture, Kamogawa City, Japan), around 100 km to the south-east of Tokyo. The name Ōyama (big [ō] mountain [yama]) is derived from Mt. Ōyama (with a shrine on its peak) and Senmaida stands for thousand [sen] pieces [mai] of paddy fields [da]: 'Thousand pieces of paddy fields located in the mountainous area'.

Next hamlet to Ōyamasenmaida is Kogane (Fig. 1, left upper corner) with fewer than 20 households. Kogane is part of Hiratsuka (165 households, 532 inhabitants in 2002), which is one of the six villages situated around Mt. Ōyama[31]. The terraces extend on a south-east slope over an elevation difference from 80 to 150 m above sea level and vary in their size between 20 and 900 m^2.[30] The rice-terrace complex of Ōyamasenmaida counts 375 rice terraces on an area of 3.5 ha; the Ōyamasenmaida Preservation Association (PA) covers adjacent fields and operates 415 plots (4.5 ha)[30].

Around two-thirds of the terraces are cultivated with rice (one-half each landowner's and Ownership System) (unpublished data). The remaining third is abandoned or rather a small part is used as orchard.

In 1999, the tanada landscape of Ōyamasenmaida became designated by the Japanese Ministry of Agriculture, Forestry and Fisheries as one of the 'Top 100 Terraced Paddy Fields of Japan'[23]. The policy behind this nomination was to direct the population's attention to the rice-terrace landscapes of Japan[32].

Methods

The field research for this paper was conducted over 50 days from December 2004 to May 2006.

As the research topic has exploratory character and concerns a contemporary phenomenon within its real-life context without distinct boundaries between context and phenomenon, a case study approach was chosen[33]. The methods adopted for data collection were participatory observation (PO)[34], personal communication (PC), semi-structured expert interview (EI) and questionnaire-based survey (QS).

PO and PC

Between December 2004 and May 2006, the first author participated in different activities in Ōyamasenmaida: e.g., assembly of the PA, several tenants, meetings, rice planting, seasonal traditional cultural events or ordinary workday life of the PA staff and local people. In the PO process (which includes all sense)[34], daily conversation with tenants (tenants A, B, D, F), supporters, staff members and land owners was a very important way for information gathering. Major support came from the PA staff members and main supporters. Complex topics of conversations were accompanied by interpreters, such as English-speaking research colleagues, tenants, supporters or members of the PA.

Semi-structured EI

About 6 months after the start of the field work in June 2005, the director of the PA, who is also the head of the Ownership System, was interviewed. The face-to-face EI was based on semi-structured interview guidelines. A Japanese PhD student who studied the vegetation of Ōyamasenmaida helped with the interview as interpreter. In November 2005 and January 2006, a long-lasting tanada ownership tenant (tenant A) was interviewed twice in a semi-structured EI.

Questionnaire-based survey

Based on the experiences of interviews and PO, structured questionnaires were designed in order to gather more detailed information regarding the PA, the Ownership System and its members. Target groups of the questionnaires were

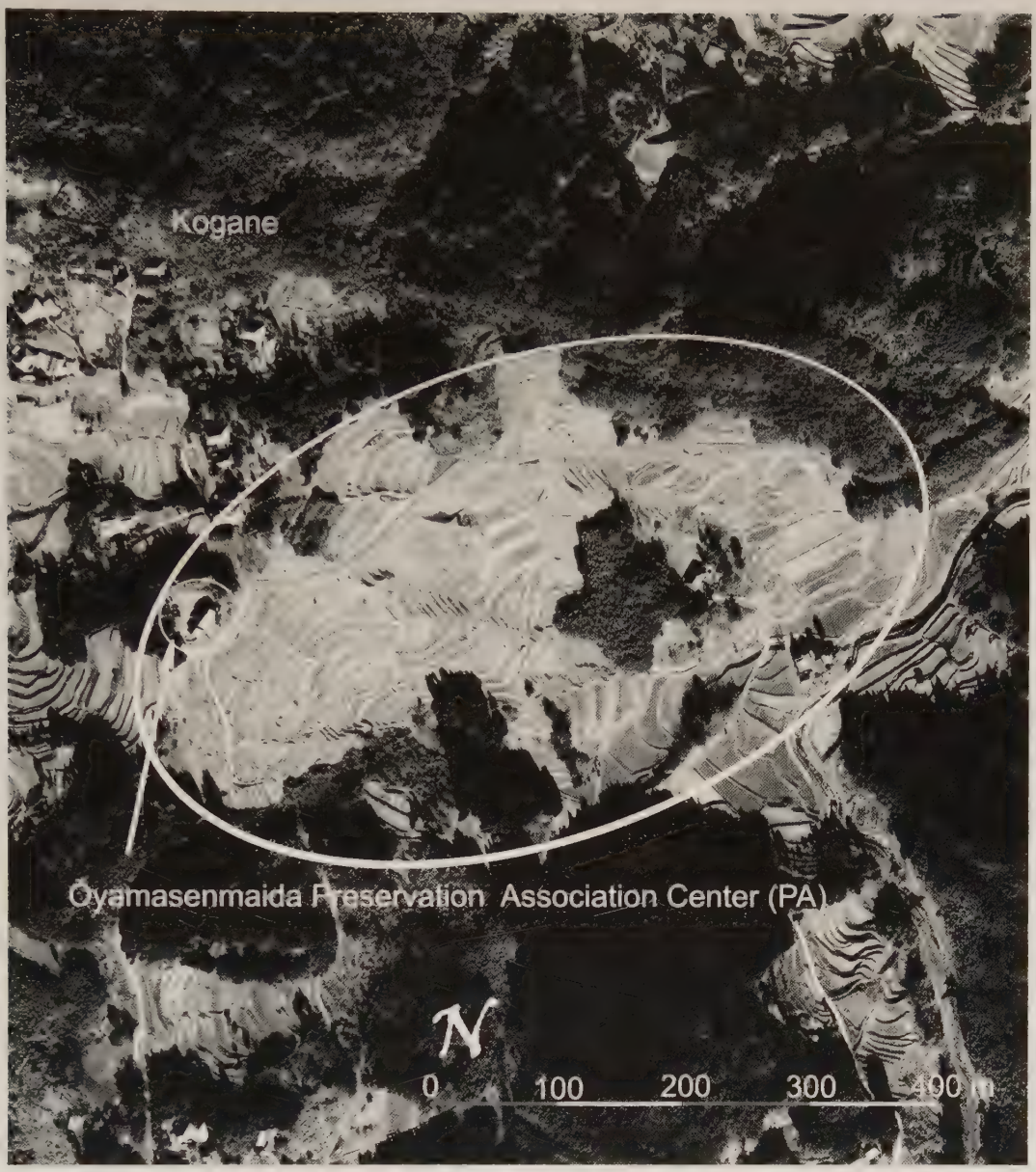

Figure 1. Aerial photo of the area of Ōyamasenmaida, taken on January 15, 2004; source: Keiyō Survey Co.

the eight landowners of the rice terraces, the 30 main supporters of the Ownership System and the 453 tenants.

For the questionnaire, the paper form was chosen, since e-mail addresses were not known in most of the cases. The structured questionnaire included behavioral, attitudinal and classification questions, which were asked in open, semi-closed and closed style.

The questionnaires were adapted for each of the three groups and distributed in spring 2006. They had been written in English and translated afterwards into Japanese. The open answers in the questionnaires had to be translated back from Japanese to English.

The cover letter gave a short introduction and explained the reason for the survey. With some additional sentences, the head of the Ownership System motivated the tenants to participate.

Tenants. Participation lists and addresses were provided by the PA office. The questionnaires (complete inventory count) were distributed out personally in tenant meetings or sent out (together with a stamped reply envelope) to those not attending. The response rate was 55% (see Fig. 2).

Landowners and main supporters. The questionnaires were personally handed out at the general meeting of the PA. To those not attending, the questionnaire was delivered personally by the PA staff or sent by post (together with a stamped reply envelope). Response rate was 38% and for the main supporters 37% (see Fig. 2).

The results from the questionnaire surveys, the EIs, observation notes and PC in field, as well as the information gathered from up-to-date documents, web sites, official statistics and secondary data, were triangulated for

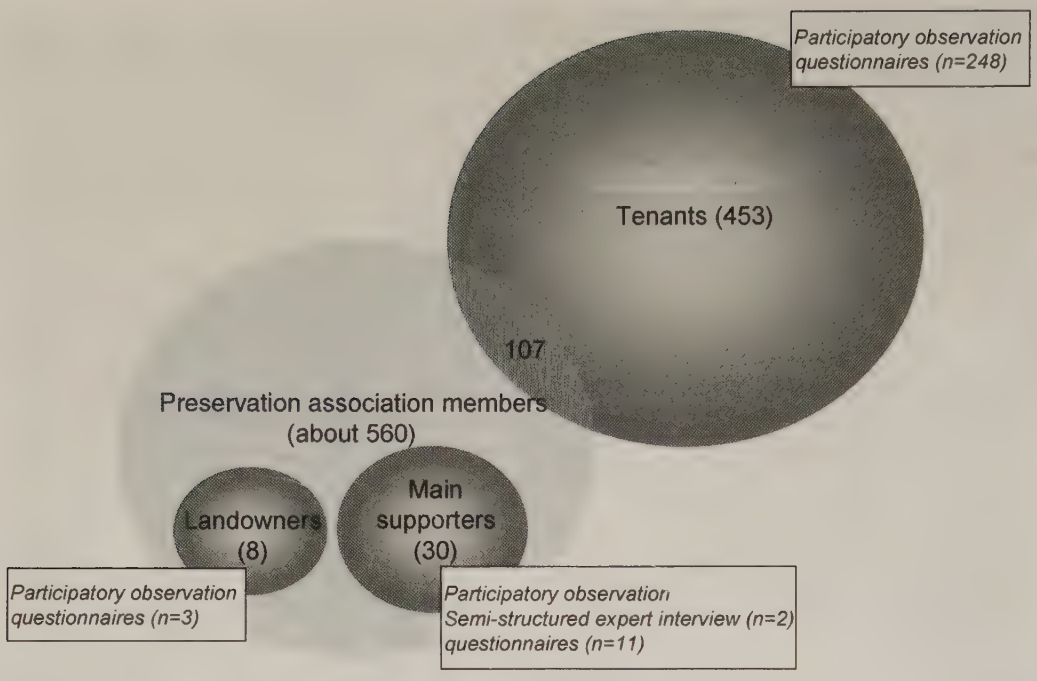

Figure 2. Members of the PA and the Ownership System, methods of data collection and return rate of the questionnaires; source: EI: June 18, 2005; PC: August 2, 2009.

validation and if necessary counterchecked by additional e-mail or phone conversation after the field-research period.

Results

Reasons for the foundation of the PA

In 2006, the rice terraces of Ōyamasenmaida belonged to 11 proprietors, all of them part-time farmers (PC: director, June 18, 2005). While three of them were still of working age, the remaining eight had already retired (ibid.). In 1997, these eight senior landowners founded, together with other farmers and local people, the NPO 'Ōyamasenmaida Preservation Association', as for all of them, these rice terraces were something special which they wanted to preserve from abandonment and decay: '*We hope, that the landowner's children will continue the husbandry of their parents in their retirement. But even if they won't do so, it is not a problem. The system is also survivable without farmers, because the management of the rice terraces is done by the Ōyamasenmaida Preservation Association group*' (PC: director, June 18, 2005).

After having established the PA, their members decided that an Ownership System, which they had heard about being applied in other regions in Japan, would be also an ideal instrument for Ōyamasenmaida (PC: director, June 18, 2005). Therefore, they initiated in 1997/1998 the 'Ōyamasenmaida Tanada Ownership System': '*The area of Ōyamasenmaida has many disadvantages, as a strong depopulation, very small scale uneconomical paddy fields on a steep inclination and a highly aged population. These factors can't give much power to the region. So we thought about, how we can change these disadvantages into advantages. We think that a Tanada Ownership System is the right way for that, because the small size of the paddy fields is still big enough for city dwellers to cultivate it. The old farmers, even if they may not have so much power any more, they however posses a lot of knowledge to offer to the city people. In contrast, city people have a big lack of nature, pure and clean air. If we add up both disadvantages – that one of the city dwellers and that one of Ōyamasenmaida – we gain an advantage*' (ibid.).

As the tokku districts were not already established at this time, the lease-out process had to be carried out via a city (EI: director, June 18, 2005; PC: director, September 26, 2009). Ten percent of the participation fee was therefore retained by Kamogawa City for administrative tasks, 10% went to the landowners and 80% to the PA (ibid.). The contract was set until 2005 (PC: director, September 26, 2009). In 2003, Kamogawa City applied to the Japanese Ministry of Agriculture, Forestry and Fisheries to become a 'Rice Terrace Agriculture Tokku' (EI: director, June 18, 2005; PC: director, January 28, 2010). The petition was accepted in 2004 and Ōyamasenmaida started thereupon with a second Ownership System, the 'Kamogawa City Ōyamasenmaida Tanada Ownership System' (PC: director, January 28, 2010). In this new Ownership System, the PA is allowed to directly lease out their land without any loop via Kamogawa City (EI: director, June 18, 2005). About 10% of the rent goes to the landowners, the rest (90%) to the PA (ibid.). When the contract of the 'Ōyamasenmaida Tanada Ownership System' expired in 2005, it was not renewed (PC: director, September 26, 2009). The old Ownership

System passed into the new one; the two different names, however, are still in use (ibid.).

Being a member of the PA is independent from the Ownership System (PC: director, August 1, 2009). But in more than 100 cases, tenants are also PA members (Fig. 2).

With 'Ōyamasenmaida' the PA wants to show the 'ideal model' of a cultural landscape and demonstrate ways how to preserve mountainous areas (EI: director, June 18, 2005). For the PA, at least as important as planting, harvesting, mowing, etc., is the exchange and the communication among the participants themselves and between the tenants and the local people (ibid.). Therefore, social gatherings are very important (PO: e.g., karaoke evenings after farming activities 2005/2006, harvest festival October 2005). Townspeople should be aware of the problems the mountainous areas are confronted with, and they should take it seriously, because: '*Most of the Japanese population lives in cities. The government is in the city. Big and important decisions are made by city people in the cities. City people can change the government and they make money; money, which is necessary to protect the mountainous areas*' (EI: director, June 18, 2005). In order to facilitate and encourage the rural–urban communication, the 'Tanada Club house' was erected in 2000, financed by the Kamogawa City (ibid.).

In the area of Kamogawa City, besides the Ownership System in Ōyamasenmaida, six other Ownership Systems exist[35].

Budget of the PA

The budget of the PA results from the yearly membership fees, the Ownership System fees, (see below) and the attendance fee of other seasonal activities/participatory programs. Besides that, Ōyamasenmaida-related products, such as rice, soybean paste, calendars, postcards, charcoal, etc., are sold (PO: December 2005–June 2006, November 6–8, 2010). During voluntary farming days or festivals, local dishes and drinks (e.g., dandelion coffee, curry rice, o-bento [Japanese lunch] with rice balls, miso soup and pickles) are prepared by female members of the PA and sold at moderate prices (PO: working events 2005/2006, torch festival November 6–8, 2010). In addition, the seminar room of the 'Tanada Club' is rented out for meetings, workshops, etc., at the price of 400¥ (*c.* 3.5 €) h^{-1}.[36] (The conversion from Yen to Euro of all prices in this paper is based on the foreign exchange rate of the Bank Austria, June 22, 2010.) Finally, the PA receives some donation from private companies, for example, from the CSR (Corporate Social Responsibility).

From these incomes office expenses, ongoing maintenance measures, permanent staff (three people), landowners and instructors are paid. All other people (around 70 people, 30 of them can be regarded as main supporters) are working as volunteers or are paid 800¥ (*c.* 7 €) h^{-1} (EI: tenant A, January 20, 2006).

Structure and organization of the Ownership System

In 2006, the tenants of the Ownership System cultivated most of the land of the eight retired farmers (EI: director, June 18, 2005). The above-mentioned three younger landowners, however, did not allocate their land, as they still cultivated it themselves (ibid). After the field research period, three of the eight senior farmers passed away (PC: director, January 28, 2010). Their land was inherited by their children and is still part of the Ownership System. Out of the three non participating landowners, one entrusted his land to the PA, while the second sold it to the third who is still an active farmer (PC: director, January 28, 2010).

The PA offers five different ownership programs[37]:

(1) The oldest program is the Tanada Ownership System[37]. It started in 2000 as 'Ōyamasenmaida Tanada Ownership System'[37]. From initially 39 rented rice terraces, the number increased to 136 in 2002 (PC: director, December 8, 2009). The tenants of the Tanada Ownership System have not changed since that time (EI: tenant A, November 5, 2005). Every rice terrace has one registered tenant—even if he/she is participating with family, friends, colleagues, students, etc. (PO: rice planting events April/May 2005/2006). The participation fee is 30,000–40,000¥ (262–340 €) yr^{-1} per 100 m^2,[37] adjusted in proportion to the area (PC: tenant A, June 29, 2010 and tenant B, March 14, 2010). The harvested rice of all tenants is put together and then divided pro-rata (PC: tenant B, March 14, 2010).

(2) In the Soybean Trust System, a special program of the PA, which started in 2001, soybeans were cultivated on abandoned rice terraces in order to revitalize them (EI: director, June 18, 2005). In contrast to the Tanada Ownership System, tenants do not rent their own 'soy terraces', but shared them, as the focus of this program is the working event *per se*[37]. The participation fee is 4000¥ (35 €) yr^{-1} $participant^{-1}$.[37]

(3) The Tanada Trust System is a structure equivalent to the Soybean Trust (collective group rent of a rice terrace) and has existed since 2002[37]. The participation fee amounts to 30,000¥ (262 €) yr^{-1} per 100 m^2.[37] The harvested rice is divided equally; around 30 kg to each registered participant[37]. In comparison with the tenants of the Tanada Ownership System, the Tanada Trust members fluctuate more and their number changes every year (PC: director, January 12, 2007).

(4) The Rice Wine Ownership System was launched in 2004[37]. Despite its name 'Ownership System', it is rather a Rice Wine Trust System, as the tenants collectively grow rice on common paddy fields (PC: tenant B, March 9, 2010). After the harvest the rice of all Rice Wine tenants is delivered to a traditional rice wine brewery in the vicinity (PC: tenant B, December 22, 2009). Every tenant gains three 1.8-liter bottles of wine[37]. Included in the Rice Wine Ownership System, traditional rice wine drinking cups and rice wine labels

(determined by a competition) are produced[37]. The participation fee is 15,000¥ (131 €)[37].

(5) The most recent program (since 2005) is the Indigo–Cotton Trust System[37]. On an area about 2 km from Ōyamasenmaida cotton and indigo are collectively cultivated (PO: October 15, 2005). After the harvest, the cotton is yarned and clothes are woven and later dyed with indigo (PC: tenant F, spring 2006).

Apart from these five programs, other activities are offered as well, e.g., lectures on fireflies and firefly watching (PO: June 2005), bamboo torch events around the rice terraces (PC: director, January 10, 2009; tenant B, January 24, 2009; tenant D, January 18, 2008; PO: November 6–8, 2010), concerts with traditional dances performed on the rice terraces[37] [PO: Kagura performance (theatrical dance), November 7, 2010], photo award of Ōyamasenmaida for the yearly calendar (PO: contest participation, July 7, 2006), production of traditional Japanese handcrafts and dishes (PC: tenant B, December 22, 2009; PO: rice planting events April/May 2006; hand craft events October 15, 2005, December 18, 2005), volleyball tournaments in the muddy paddy fields before rice planting (PO: April/May 2006), etc.

From the number of participants and size of area, the strongest programs are the Rice Wine and the Tanada Ownership System. Indigo–Cotton and Soybean are less important.

Many participants attend more programs contemporaneously. That is why the questionnaire was sent to all participants. In the empirical inquiry, however, the focus of PO and PC was concentrated on the rice-growing tenants (i.e., Tanada Ownership System, Tanada Trust System and Rice Wine Ownership System).

Yearly schedule of a Tanada Ownership and Tanada Trust System tenant

For the 'tanada tenants', farming activities are scheduled about seven times a year, mostly with two time options: rice planting in April/May, weeding in June, July and August, harvesting and threshing in September and harvest festival in October (EI: tenant A, November 2, 2005). All other work in between (mowing or burning of the slopes, manuring, sputtering, etc.) are done by the landowners or the PA (EI: director, June 18, 2005 and tenant A, November 2, 2005).

The seven collective working days are big events and are very accurately organized. Each day starts with an attendance check at the registration desk and a welcome speech to explain the respective procedure (PO: April/May 2005/2006). Most of the tenants come by car in the morning and return the same day (PO: working events 2005/2006). The tenants who stay overnight mostly spend the night in farmers, houses for a small payment or for free, depending on how well they know each other: '*I always stay at* [...]*-san, but he is not the landowner of our* [...] *rice field. Now he does not work for tanada club. He invited me for omatsuri* [folk festival] *in private. This time, I did not go to the omatsuri but I stayed at his house and had a party. I introduced my friend, who works for a fertilizer company.* [...]*-san likes to meet people, so not everybody, but who are friends of friends, are welcome to visit his house for a stay. About payment, we always have party, eating and drinking, so I usually pay some money for dinner, like 3,000–4,000¥. He is an old man, living on pension, so that is reasonable. Anyway, this has nothing to do with tanada club. But many people meet these farmers at the tanada club and become personal friends. I guess this is also one aim of tanada club*' (PC: tenant B, August 18, 2009).

The landowners and supporters of the PA instruct the less experienced tenants (PO: working events 2005/2006). Furthermore learning from other tenants plays a role: '*For example, the landowner of my paddy is Mr.* [...]. *He taught me in the first year how to work. Now I can teach my neighbors*' (EI: tenant A, November 2, 2005). If someone cannot come to do the work on the rice field, the supporters or neighbors will do it, '*but it gives a very bad impression!*' (ibid). For a better identification in the field, the instructors wear red hats with name targets (PO: working events 2005/2006). As the tenants do all labor manually, there is no necessity for special costly equipment or machinery: '*For the work on my paddy field I only bought jikatabi* [working shoes with a thick rubber sole and a separate section for the big toe] *and a scythe*' (EI: tenant A, November 2, 2005). Cultivated rice in Ōyamasenmaida is mainly koshihikari (EI: tenant A, January 20, 2006), a very popular rice variety in Japan[38,39]. Despite the dominance of manual labor, the farming management in and around Ōyamasenmaida is not organic farming: '*Some of them* [farmers] *use machines and insert pesticides, chemical fertilizer, herbicides and insecticides, others not*' (EI: tenant A, November 2, 2005).

Provenance and age structure of the tenants, supporters and land owners

The findings presented in the following sections are based on the questionnaire surveys, mostly of the tenants (March–May 2006), but also of the supporters (May–June 2006) and landowners (May–June 2006).

From 248 responding tenants 246 are city dwellers. They live in 55 different cities of five prefectures (two answers could not be attributed) from about 50–150 km distance from Ōyamasenmaida (Fig. 3). The prefectures Tokyo, Kanagawa, Saitama and Chiba, from which most of the tenants come, are densely inhabited (with 1175–5751 persons km^{-2}, among the highest population densities of Japan; PC: Uematsu, M., Population Census Division, Statistic Bureau, MIC, May 11, 2009).

The population size of the 55 cities ranges from over 11,000 up to 8.5 million inhabitants (ibid). The biggest share of the responding tenants (58%) lives in cities with 100,000–1,000,000 inhabitants.

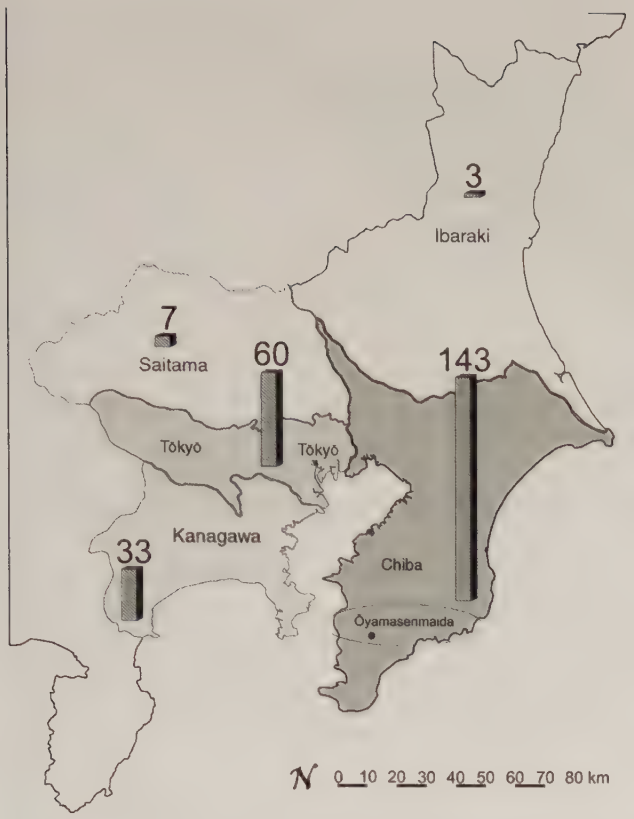

Figure 3. Provenance of the tenants (number of tenants from the relative five prefectures); map based on Bartholomew[40].

The tenants' questionnaires were answered by 75% male and 25% female tenants. This gender imbalance, however, does not imply that women are underrepresented in the Ownership System but rather that more men than women answered the questionnaire (PO: March 26, 2006).

The average age of the 248 responding tenants was 53 years (two invalid answers). Twenty percent were at least 65 years old or older. Compared with the Japanese population, this share represents the Japanese average age structure (20.1% aged 65 and older)[41]. The class '15–64 years' of the sample comprised 79% (Fig. 4), both over the Japanese average (65.8%) and that of the five prefectures[41]. The age group of 0–14 years accounts for 13.7% for the whole of Japan. In the sample of tenants this group does not appear, as children, even when participating with their parents and/or grandparents, did not answer the questionnaire (PO: working events 2005/2006).

From the 30 main supporters, 11 answered the questionnaire (three women and eight men). The average age was 64 years. The average age of the three landowners (all male), who answered the questionnaire was 76 years.

A big share of the tenants (82%) participated in the company (about three-quarters with family members, one-quarter with friends). Only 17% (43 respondents) stated that they are not accompanied (among them 11 singles and 28 married). In 50% of the accompanied respondents, the participating 'family member' was wife or husband only. The other 50% referred to different combinations of spouse,

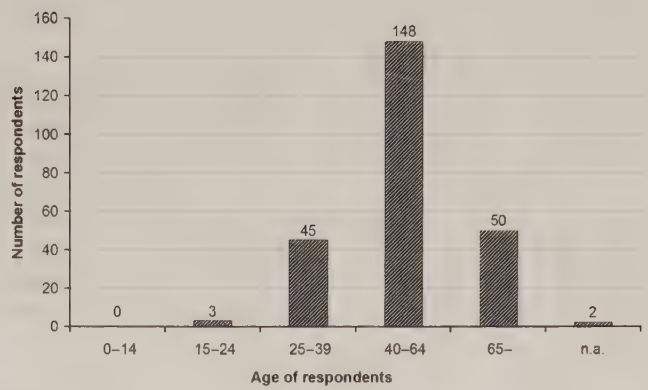

Figure 4. Age structure of the responding tenants (248).

children, parents, parents-in-law, grandchildren, son, daughter, son- or daughter-in-law.

Tenants' professional background and relation to agriculture

Out of 248 responding tenants, 63% were in employment and 32% were not in employment (49 retirees, 21 housewives, five students and four unemployed persons); 5% of the answers could not be clearly assigned. Among the persons in employment, 150 people (96%) worked in the tertiary sector, 2.6% in the secondary and 1.3% in the primary sector. The proportion of 63% employed persons among the tenants' sample is slightly higher compared to the Japanese average in 2006 (58%)[42]. The share of tenants working in the tertiary sector is significantly higher (96%) in contrast to the Japanese average (67.2%) in 2005[43] and, similarly, the share of tenants of 60 years or older who are still in employment (39 versus 15% Japanese average[42]).

One question addressed in the tenants' questionnaire was: '*How was your relation to agriculture, before attending the activities in Ōyamasenmaida*?' From 251 valid answers (multiple answers were possible; three tenants abstained from answering), 65% stated that they had no connection before, whereas 16% were directly descended from agricultural families or had farmers as relatives (such as parents-in-law, grandparents). In each case, 4% had a farmer as neighbor, visited the countryside at the weekends or grew their own vegetables in kitchen gardens. The remaining 20 answers were very diverse, for example: '*I collect materials about agriculture for my picture books*', '*Produce a musical with the theme on a farming village*', '*When we become 40 years, we would like to become farmers*', '*I worked as a university professor in the field of agriculture for many years*', '*I am alumnus of a Japanese University, Faculty of Agricultural Sciences*'.

Tenants' motivation

When asked for the main reason for their participation in the Ownership System, the most common answer was '*Because I like tanada*' (Fig. 5). This question was asked in

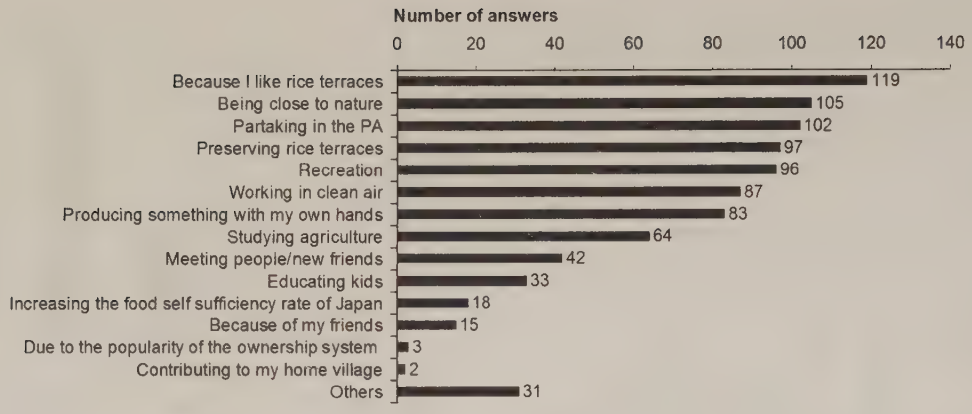

Figure 5. Tenants' motivation for participation (897 valid answers from 237 persons).

a semi-closed style: 14 response options were given and there was also the possibility to add further motivations. The tenants could indicate a maximum of five motivations. From 248 respondents, three abstained from voting and eight selected more than five answers and were therefore rejected.

Among the 31 additional motivations (Fig. 5), nine concerned the interest in rice wine, soybean and/or indigo. The remaining answers were unique, e.g., '*In order to compose haiku*' [Japanese poetry], '*Convalescence from a mental illness*', '*In order to understand Japanese culture through rice cultivation*'.

Relevance of cultural landscapes and ways to maintain it

For 58% of the 248 tenants surveyed, cultural landscape was very important, for 28% important, for 9% less and for 1% not important at all. Nine persons (4%) did not answer this question.

Regarding the question, how to conserve the traditional cultural landscapes, 8% would be willing to pay more taxes, 9% to donate money for farmers once a year and 15% to pay higher prices for farm products. Working as a volunteer once a year (47%) was the most accepted measure to support traditional cultural landscapes. Only 1% of the respondents saw the current landscape development as satisfying.

Discussion

If we try to compare the Japanese Ownership System with similar activities in Europe, North America and Australia (Table 1), we can make out two rough categories of hobbyist, voluntary work on farm land:

(1) 'Self-harvest' projects in several European cities, allowing the urban population to grow their own vegetables on leased farm land.
(2) Volunteers collectively participating in landscape stewardship and nature conservation on farm land.

In the self-harvesting project, well analyzed by Vogl et al.[44], 861 self-harvesters cultivate plots of 20, 40 or 80 m^2 of arable land, prepared and sown by 12 organic farmers in Vienna.

Conservation volunteers are organized on local, national or even international level as civil society movements and work on farm land[45–47]. There are also corporate volunteering and (semi-) commercial organizations placing individual volunteer tourists on organic farms or in nature conservation projects worldwide[48,49].

Common ground between all three forms of voluntary work on farm land

Despite the different geographic contexts and diverging forms of organization, there are astonishing similarities in the motivation. Common to all three forms of voluntary work is that they clearly reflect the shift from food production to consumption of recreation, landscape stewardship, meditation and education (Table 1). In rural geography and sociology, this fundamental pattern of rural change has been discussed under the notion of consumptive or post-productivist countryside[56,57].

Although detailed socio-demographic data are missing, the comparison of the case study results with the literature on self-harvesting and conservation volunteers clearly indicates that the volunteers are not a particular group in terms of socio-demographic characteristics (apart from maybe higher-education level and urban background), but they share similar values and norms, such as the pleasure of socializing, readiness to work manually, and the will to contribute to common goals such as nature or landscape conservation[47,58].

Ownership System versus self-harvesting

Self-harvesting clearly differs from the Ownership System by its individualistic approach, focusing on organic food production, on individual learning and innovations.

The self-harvesters live much closer to the plots (on average 1.8 km[44]) and work on them much more often. They come and go according to their individual schedule, make their own choice of plants and there is even a kind of

Table 1. Comparison of the differences and commonalities among the Ownership System, self-harvesting and conservation volunteering.

Features	Ownership System	Self-harvest initiatives	Volunteers in landscape stewardship and nature conservation
Context	Japan	Austria and Germany[44,51]	Worldwide[45–47,49,50]
Land use	Mainly rice	Vegetables and herbs[44,51]	Grassland, wet lands, orchards, hedges and 'natural' landscapes as, e.g., the rain forest[46,47,50]
Nature of activity	Collective	Individualistic[44,51]	Collective[46,47,49,50]
Main activity	Conventional/traditional food production, preservation of cultural landscape	Organic food production[44,51]	Landscape stewardship, nature restoration, nature monitoring[45–47,49,50]
Motivations of the volunteers	Rice-terrace landscape, being close to nature, preservation, recreation, working outdoors, manual labor, studying agriculture, meeting people, educating children (Fig. 5)	Own organic vegetables, resting and meditating, talking with other self-harvesters, picnicking, playing with children, walking around, nature watching, reading a book, sunbathing or taking photographs[44]	Fascination with nature, accomplishing something in a group without hierarchy, physical fitness and health, socializing with like-minded people, slipping into different world, personal growth, living authentically, doing something useful, recreation, learning[45,46,50,52–54]
Fees	262–340 €/100 m^2 yr^{-1} for a Tanada Ownership System tenant in Ōyamasenmaida[37]	313–375 €/100 m^2 yr^{-1} (Austria)[55] 176 €/100 m^2 yr^{-1} (Germany)[51]	Voluntary tourists pay agency fees; volunteers in other voluntary organizations do not pay[45,47,49]
Origin of initiative	First (Tanada) Ownership System 1992 in Shikoku; since 2000 in Ōyamasenmaida, initiated by the local PA (founded in 1997 by local landowners and citizens)[30]	1987 by an Viennese organic farmer and Regine Bruno from the Environmental Advisory Service, in reaction to the Chernobyl disaster[44,51]	Volunteer Stewardship Network created in 1983; many amateur associations for the pursuit of natural history, founded during the 19th century[45,46,49]
Origin of volunteers	City dwellers from about 50 to 150 km distance	Urban and rural people from a distance of 1.8 km in average[44]	International and local volunteers[45–47,49,50]
Age of volunteers	All age groups	Most between 30 and 50[44]	
Professional background of volunteers	Rather well-educated people (96% of the employed tenants work in the service sector), as working in the tertiary sector jobs, generally requires higher qualifications. Apart from that are 39% of the tenants of 60 years or older still in employment. This might be another indication for comparatively higher-qualified positions	Comparably well educated[44]	All groups of society[47]
Frequency of participation	~7 times (days) yr^{-1}	On average 2.6 times a week with big variations[44]	From once a year to more than once a week[46,47]
Know-how and skills	Primarily formal instructions in the morning and professional supervision during the whole day	Individual learning by doing, learning from neighboring tenants[44,51]	Collective restoration and stewardship activities supervised by more experienced volunteers and professionals; individual monitoring activities[45–47,49]
Innovation in cultivation	No intention for innovation in cultivation, methods or varieties	Trying something new, such as exotic plants, new cultivation methods, organic production[44]	n.a.
Property rights	Retired farmers lease out nearly all of their rice terraces, the rest is cultivated by themselves or falls abandoned; 90% of fees stay within the PA, only 10% goes to the landowners	Active farmers directly lease out small parts of their arable land to tenants, the rest is cultivated by themselves; 100% of fees goes to farmers; farmers' profit can be between 12 or 39 € per working hour (for 30 or 39 plots)[44,51]	On private and state land, sometimes use agreements with land owners[47]
Infrastructure	Big club house with showers and toilets	Children's playground, benches, toilets[44,51]	n.a.

ambition to plant exotic/rare plants which the neighboring plots do not have[44]. In contrast, the Japanese tenants meet for around seven collective working days a year for synchronized planting, weeding and harvesting the same variety of rice.

All of the self-harvesting farms just offer a small share of their land for rent, whereas the retired Japanese landowners lease out nearly everything. The continuity of (the rice) cultivation and the conservation of the landscape scenery is their main motivation. Austrian farmers contrarily are also motivated by economic advantages. An agricultural journal targeted to farmers in Austria and Germany[51] promotes self-harvesting with hourly revenue rates from 12 to 39 € per working hour invested by the farm family (100% of the rent goes directly to the farmers). In Japan, only 10% of the tenant's rent goes to the farmers, the rest to the PA. Moritz[51] also points out the advantage for farmers of the self-harvesting system of having the rent in their bank account before harvest time and without any weather risk. Direct marketing of farm products to self-harvesters also contributes to the farm income[44].

Neither Japanese nor Austrian tenants are motivated by producing cheap food. It is rather about producing something you cannot buy at supermarkets: self-cultivated and harvested food. The self-harvest initiative can be seen as an organic local food system in reaction to the Chernobyl disaster[51]. The Ownership System, however, is based on conventional food and might be a consequence of false labeling scandals in the 1980s and 1990s and a general mistrust in the globalized food system in Japan. In the mid-1990s—parallel to the Ownership System—a local food movement called chisan–chisho (literally translated as 'locally produced, locally consumed') appeared and sprouted all over Japan[59,60]. Local food is perceived by the Japanese as safer, more delicious, trustworthy, environmentally friendly and as a means of boosting the local economy[61].

Ownership System versus conservation volunteering

Mühlmann et al.[47] and Bell et al.[45] categorized different types of voluntary conservation organizations:

- Local associations supporting the stewardship of their local landscapes as their place of living and recreation.
- Predominately urban voluntary tourists engaging in restoration projects or on organic farms, i.e., for landscapes outside of their living environment.
- Corporate volunteering activities.

An example for the first type is the 'Aktion Heugabel' in Austria, where local non-farmers help farmers to conserve the local landscape with its extensively managed grasslands[41]. The second group of organizations place volunteers on organic farms (e.g., 'WWOOF': World Wide Opportunities on Organic Farms) or into conservation projects worldwide[49]. An example for corporate volunteering is the company 'swiss.com' which organizes the so-called 'Nature-Action-Days' in cooperation with the WWF (World Wide Fund for Nature), where employees can engage in landscape stewardship, e.g., mowing wet meadows[47].

Apart from most of the local associations, the engagement tends to be short term. Work holidays or landscape stewardship days are time limited and confined to a particular area. This reflects a general trend in Western voluntary organizations: away from lifelong participation toward targeted and temporary engagement[62]; long-term membership becomes less attractive[63,64]. Local clubs, who are committed to the long-term cultivation of endangered landscapes (such as wet meadows) are based on volunteers, motivated to take care for the landscape they live in. But they also have difficulties in finding young members, willing to engage for a longer period[49]. This development in conservation volunteering is in contrast with the long-term urban–rural coalition of the Japanese Ownership System.

In contrast to the Ownership System, wherein the production of own rice is an important element, food production does not play any role in the voluntary conservation activities.

Social experience, however, and the management of relations between experts and professionals on the one hand and amateurs on the other hand[45] are motivating factors in both schemes.

Conclusions

The Japanese population highly values traditional cultural landscapes for tradition, culture, identity, biodiversity, quality of life and recreation. In the context of unwanted landscape changes caused by agricultural land abandonment, urban dwellers take over the responsibility for landscape stewardship. They invest time, manual labor and money to support the conservation of the traditional cultural landscape.

In contrast to self-harvesting initiatives in Europe concentrating on organic food production or volunteering focusing on nature conservation, the Japanese Ownership System combines:

- the volunteers' efforts for the common 'good' landscape;
- the individuals benefit by producing their own local food.

The success of the Ownership System might be explained by the fact that motivations for common purposes such as landscape conservation work are supported by individual benefits, such as rice or social benefits.

The urban tenants of the highly urbanized Japanese society appreciate the opportunity to accompany all steps of food production and its consumption, the sensual perception of nature, seasons, weather, phases of growth and decay, new experiences or positive effects on the education of their children. The practical rice cultivation is also, for many, a way to come closer to culture and tradition. The long-term rural–urban cooperation does not only yield

satisfaction to the urban volunteers, it is highly beneficial for the conservation of agro-biodiversity and the cultural landscapes. And last but not least, the local landowners are valued and can hand on their experience and skills and thus still contribute to the cultivation of their land despite their retirement age.

A comparison with the European self-harvesting initiatives and conservation volunteering in North America, Australia, North and Central Europe demonstrates that the Ownership System is special because of its collective nature and long-term institutionalized involvement (see Table 1). However, all those forms of voluntary work on farm land reflect a clear shift from food production in the postwar period to non-productive motivations such as nature conservation, education and leisure.

In Japan, the widely spread Ownership Systems are perceived as a promising way of stopping or slowing down the process of land abandonment. However, it remains unclear whether it will help Japan to engage non-farmers to take up farming as a profession, which is also one of the objectives of the Ownership System. It might be one of a bundle of measures to keep up agricultural land use also in the less favored mountainous areas.

Technically, the Ownership System can be transferred to any kind of traditional land use that is characterized by manual labor and the production of some commodity, as for example, wine in wine terraces, or fruits in traditional orchards. The 'conserving' areas, however, should be close to urban agglomerations. Given that the prospective tenants should be able to produce and use their own products, one of the most threatened elements of rural landscapes in Austria—low-productivity grasslands, which are endangered by abandonment and/or afforestation—are not suitable for the Ownership System, as grass and weeds cannot be eaten. From the social-organizational point of view, the long-term urban–rural collaboration poses a challenge for transferability. This stands in clear contrast to tendencies in Europe, Australia and North America where citizens are reluctant toward a long-term commitment to an organization[61]. They tend to favor project-based short-term activities, combining the need to do something useful with the need for recreation and socializing.

Acknowledgements. This paper is an outcome of a PhD project. The research in Japan was funded by the Ministry of Education, Culture, Sports, Science and Technology of Japan (MEXT) and the German Academic Exchange Service (DAAD). The authors would like to express their deep gratitude to the Ōyama-sanmaida Preservation Association for providing information and supporting this survey, especially to Mitsuji Ishida, Yoshiko Sudo, Hitomi Taira and to all participants of the Ownership System, which agreed to participate in the questionnaire poll. We are beholden to Drs Nobuhiko Sawai, Kentaro Aoki and Ayako Toko, who assisted in the translation process of the questionnaires. Sincere thank also to Professor Dr Wolfgang Holzner, PhD superviser of Pia Kieninger, for encouraging the studies for this paper. Thanks to the colleagues of the Institute of Nature Conservation Research (BOKU University) as well as to the anonymous reviewers and the editors of RAFS, for their valuable annotations to this paper.

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Renewable Agriculture and Food Systems: 26(4); 342–353 doi:10.1017/S1742170511000147

Labile carbon and other soil quality indicators in two tillage systems during transition to organic agriculture

David Bruce Lewis[1]*, Jason P. Kaye[2], Randa Jabbour[3], and Mary E. Barbercheck[3]

[1]Department of Integrative Biology, University of South Florida, Tampa, FL, USA.
[2]Department of Crop and Soil Sciences, The Pennsylvania State University, University Park, PA, USA.
[3]Department of Entomology, The Pennsylvania State University, University Park, PA, USA.
*Corresponding author: davidlewis@usf.edu

Accepted 10 March 2011; First published online 20 April 2011 **Research Paper**

Abstract

Weed management is one of the primary challenges for producers transitioning from conventional to organic agriculture. Tillage and the use of cover crops are two weed control tactics available to farmers transitioning to organic management, but little is known about their interactive effects on soil quality during the transition period. We investigated the response of soils to tillage and initial cover crop during the 3-year transition to organic in a cover crop–soybean (*Glycine max*)–maize (*Zea mays*) rotation in the Mid-Atlantic region of the USA. The tillage treatment contrasted full, inversion tillage with moldboard plowing (FT) versus reduced tillage with chisel plowing (RT). The cover crop treatment contrasted annual versus mostly perennial species during the first year of the rotation. The experiment was initiated twice (Start 1 and Start 2), in consecutive years in adjacent fields. By the end of the experiment, labile carbon, electrical conductivity, pH and soil moisture were all greater under RT than under FT in both starts. Soil organic matter and several other soil attributes were greater under RT than under FT in Start 1, but not in Start 2, perhaps owing to differences between starts in initial field conditions and realized weather. Soil attributes did not differ between the two cover crop treatments. Combining our soils results with agronomic and economic analyses on these plots suggests that using RT during the organic transition can increase soil quality without compromising yield and profitability.

Key words: agroecosystem, base cations, conductivity, cover crop, matric potential, pH, phosphorus, soil moisture

Introduction

The use of reduced and conservation tillage in agroecosystems has grown dramatically since the mid-20th century owing to concerns that intensive tillage has adverse consequences for soil conservation, water quality and production costs[1,2]. Tillage equipment, such as moldboard plows, inverts soil, and potentially buries surface residue, hastens erosion, depletes soil organic matter (SOM) and nitrogen (N), reduces structural and aggregate stability and reduces soil biodiversity[3–13]. One notable effect of inversion tillage is the loss of near-surface soil carbon (C), mainly from the labile (bioavailable) fraction[14–18]. Reduced tillage (RT) is a compromise that may provide some weed suppression with fewer adverse effects on soil, as RT equipment such as chisel plows loosens soil without inverting it.

Organic management is an increasingly practiced form of sustainable agriculture that presents many perceived health, environmental and economical benefits[19–25]. Owing to the prohibition on the use of biocides, many organic farmers use inversion tillage (also referred to as full tillage) to control weeds[26–29]. This reliance on full tillage (FT) is paradoxical, given the emphasis of organic agriculture on enhancing soil quality[27]. Soil quality is often higher on organic than on conventional farms that use synthetic chemicals[30–36]. Yet these benefits may depend on tillage practices, as soil comparisons between RT and FT plots on organically managed farms[37–42] generally confirm discoveries from conventionally managed farms, cited above. The development of profitable organic systems that employ reduced or zero tillage thus remains a critical goal in sustainable agriculture[43–47].

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Crop rotation is another weed control strategy[48] that affects soil attributes. Many rotations include cover crops that create surface residue, reduce erosion, suppress weeds, improve soil physical structure, build nutrient and SOM pools, and attract beneficial mesofauna[33,49–52]. Each cover crop species (or species mixture) provides these multiple services to varying degrees, resulting in different effects on soil structure, hydrology and biogeochemistry[53]. Cover cropping strategy could thus be an additional factor in tests of RT on organically managed farms.

Reduced tillage, cover cropping and organic management are all important strategies for improving soil quality. Integrating the three can be challenging, however, particularly during the transition to organic production when growers often experience pest emergence, high weed growth and reduced yields[54,55]. In this paper, we compare soil quality in different tillage (RT versus FT) and cover crop (annual grain versus mainly perennial forage) treatments during the 3-year transition period required for organic certification in the USA. Our primary focus was on the response of labile C in soil because it is often used as a metric of soil quality[35,56,57], is directly linked to plant-available nutrient turnover[58] and is a sensitive indicator of management impacts on soil C sequestration[59,60].

We predicted that relative to RT, FT would result in soils with less labile C, because soil inversion enhances decomposition[61] and reduces capture of new organic C[62]. With respect to cover crops, we expected labile C to be greater in the perennial forage treatment than in the annual grain treatment since the perennial system forms sod. We expected cover crop effects to diminish as the experiment progressed, because we only included cover crops during the first growing season. We sampled soil for other chemical and hydrological metrics of soil quality that are known to affect crop yield. Based on previous studies[63], we expected these other metrics also to increase under RT relative to FT, as FT may mobilize soluble, charged constituents in leachate[64–66], and reduce water-holding capacity owing to SOM loss. Finally, we link our soil quality results with companion studies from the same plots[67–69] to develop an agroecosystem management perspective that considers how tillage affected soils, weed growth, pest biocontrol agents, crop yield and profitability.

Methods

Site

The field experiment was conducted at the Russell E. Larson Agricultural Research Center near Rock Springs, PA, USA (lat. 40.712°, long. −77.944°, 350 m elevation), with a continental climate of 975 mm mean annual precipitation and mean monthly temperatures ranging from 3°C (January) to 22°C (July). Summer precipitation (April–August) during 2004–2007 was 659, 333, 420 and 425 mm, respectively[69], compared with a long-term average of 483 mm (1953–2007, State College weather station, National Climatic Data Center). Soils are Hagerstown silt loam (fine, mixed, semi-active, mesic, Typic Hapludalf) and Murrill channery silt loam (fine-loamy, mixed, semi-active, mesic Typic Hapludult). During the preceding 3 years, the site had been managed non-organically with a tomato–wheat rotation, with tomatoes grown in the year before our experiment began. Previous management included only non-organic crop production since the 1960s, when the land was purchased from a local farmer.

Experimental design

The experiment was managed according to US organic certification regulations[70], and was conducted during the 3-year period from terminating conventional management to receiving organic certification. The 3-year rotation comprised cover crops in year 1, soybean (*Glycine max* (L.) Merr.) in year 2 and maize (*Zea mays* L.) in year 3. The 2×2 factorial design crossed two tillage approaches with two first-year cover crop mixtures. The two tillage approaches were RT with a chisel plow that disturbed (but did not invert) soil to a depth of 15 cm, versus FT with a moldboard plow that fully inverted the top 23 cm of soil. In both tillage treatments, soil was further disturbed to a depth of 2–6 cm with a rotary hoe, and 7–10 cm with a field cultivator. The RT–FT contrast was first imposed during the switch from cover crops to soybean. The two cover crop mixtures were an annual group comprising rye (*Secale cereale* L.) followed by hairy vetch (*Vicia villosa* Roth), versus a mainly perennial group comprising timothy (*Phleum pratense* L.), oat (*Avena sativa* L.) and red clover (*Trifolium pretense* L.). The cover crop contrast was only imposed in the first rotation year, although its effect on soil attributes is examined for all three years.

The experiment was established twice, first in autumn 2003 (Start 1), and again in autumn 2004 (Start 2) in an adjacent field. The three growing seasons for Start 1 were 2004–2006, and for Start 2 were 2005–2007. In the year (2004), before initiating Start 2, the Start 2 field was planted with timothy, oats and red clover. Start 2 was tilled more often than Start 1 owing to difficulties controlling perennial weeds; nevertheless, the FT plots were tilled more frequently and more intensely (deeper and with soil inversion) than were the RT plots in both starts (Table 1). Smith et al.[68] provide a schedule of additional farm operations including seedbed preparation, sowing, and harvesting.

In October 2003, liquid dairy manure was applied at a rate of 4480 kg ha^{-1}, and lime was applied at 1120 kg ha^{-1}. Liquid manure fertilizer at this research center is typically 8.2% solids by mass, and has elemental concentrations by wet mass of 0.4% N, 0.05% phosphorus (P) and 0.3% potassium (K). Compost (grass clippings, leaves and food waste) with 78% solids and elemental concentrations by wet mass of 2% N, 0.4% P and 0.9% K was added in the autumn of rotation year 1 at a rate of 17,920 kg ha^{-1}. Finally, in March of rotation year 3, bedded cattle manure

Table 1. Schedule and number of tillage operations in each combination of start, cover crop and tillage regime. Each tillage event is denoted by an X. (Rye-vetch, initial cover crop of rye followed by vetch. Timothy, initial cover crop mixture of timothy grass, oats and clover. RT, reduced tillage with chisel plow. FT, full tillage with moldboard plow.)

	Start 1				Start 2			
	Rye-vetch		Timothy		Rye-vetch		Timothy	
	RT	FT	RT	FT	RT	FT	RT	FT
2004								
Aug	X	X						
Sep					X	X		
2005								
Apr								
May		X	X	X				
Jun								
Jul								
Aug								
Sep					X	X		
2006								
Apr		X		X		X	X	X
May								
Jun								
Jul								
Aug								
Sep								
2007								
Apr					X	X	X	X
No. till events	1	3	1	2	3	4	2	2

with 38% solids and elemental concentrations by wet mass of 0.5% N, 0.2% P and 0.5% K was applied to Start 1 at a rate of 46,063 kg ha^{-1}, and to Start 2 at 32,199 kg ha^{-1}.

The field for each experimental start was organized in a randomized complete block design with one replicate of each treatment in each of four blocks ($n = 4$ treatments $\times$ 4 blocks = 16 plots per start). The block array was perpendicular to the boundary separating the Hagerstown and Murrill portions of the fields. Each replicate (plot) measured 24 m $\times$ 27 m (0.065 ha). The combined area of the two starts was surrounded by a 7-m wide grassy border that was routinely mowed. To ensure relevance to organic feed-grain cropping systems typical of the Mid-Atlantic region, a farmer advisory board composed of local growers helped to guide the crop sequence and management decisions throughout the experiment.

Soil sampling

We collected two sets of soil samples, one for quantifying chemical and hydrological metrics of soil quality, and one for quantifying soil bulk density. In the first set, we sampled each plot in the fall of year 0 prior to implementing experimental field treatments, and then four times per year (May, June–July, August, and September–October) during each rotation year. On each sampling date, we collected three composite samples from each plot. Each composite comprised 15 cores (each 2.5 cm diameter $\times$ 15.2 cm deep) taken around a random point and thoroughly mixed by hand. Each composite sample underwent laboratory analyses, and the data were then averaged across composites prior to statistical analysis, yielding $n = 1$ value per plot and date for each soil attribute. To estimate soil bulk density, our second set of samples was volumetrically collected with a hammer core from the 0–10, 10–20 and 20–30 cm depth ranges on two occasions: at the end of rotation year 1 and at the end of rotation year 3. On each date, soil was collected from two random locations per plot, again with data averaged to the plot level, yielding $n = 1$ bulk density value per plot and depth on each date.

Laboratory soil analyses

The first sample set was analyzed for soil quality metrics. Labile C, gravimetric soil moisture and matric potential were expected to be dynamic, and were thus quantified for each of the 12 collection dates during rotation years 1–3. We expected less temporal variability from other soil attributes, and so they were quantified for fewer dates. Base cations, SOM, cation-exchange capacity (CEC), pH and bioavailable phosphorus (P_{av}) were analyzed on May samples only, whereas electrical conductivity was analyzed from mid-summer (June–July) and autumn (September–October) samples only. Soil pH was additionally analyzed on the final samples collected in autumn of year 3. Concentrations of zinc (Zn) and copper (Cu) were determined only from samples collected in May of rotation year 3. A subset of these soil attributes was quantified from the initial pre-experiment samples collected in the fall of year 0.

We define labile C as organic C oxidized by a permanganate solution[57]. For each sample, we combined 5 g of air-dried, sieved (2 mm) soil with 20 ml of a permanganate solution. The permanganate solution contained 0.02 M potassium permanganate ($KMnO_4$) and 0.1 M calcium chloride ($CaCl_2$), and was adjusted to pH>7.2 using sodium hydroxide (NaOH). After shaking and settling the soil–permanganate slurry, 0.2 ml of supernatant was thoroughly mixed with 9.8 ml of deionized (DI) water. This diluted supernatant was read spectrophotometrically (Spectronic 21 D, Milton Roy), and the reduction of permanganate was quantified as the decline in light absorbance at 550 nm. We assumed that 9 mol of organic C were oxidized for every 1 mol of permanganate reduced.

Soil matric potential was determined using a filter paper method[71]. Oven-dried filter paper (Whatman no. 42) of known mass was sealed for 48 h in a plastic bag containing 250 ml of soil. The moisture-equilibrated filter paper was then recovered, cleaned and reweighed to obtain filter percent water, which was converted to matric potential following the relationship $\ln \Psi_m = -2.397 - 3.683 \ln F$, where

Table 2. Initial soil conditions in each experimental start. (A) Late autumn of the year prior to the initiation of the experiment. (B) May of rotation year 1. Cell values in the 'Start' columns are means (and standard errors of the means). Standard errors and *P* values are based on $n = 32$ plots, with 16 plots in each start. *P* values compare means between starts.

Variable	Start 1	Start 2	*P*
A. Late autumn pre-experiment			
pH	6.71 (0.03)	6.99 (0.04)	<0.001
P_{av} (mg kg^{-1} soil)	52.4 (3.4)	38.1 (1.9)	0.001
K (mg kg^{-1} soil)	197 (4)	141 (6)	<0.001
Mg (mg kg^{-1} soil)	167 (2)	193 (4)	<0.001
Ca (mg kg^{-1} soil)	1650 (50)	1640 (40)	0.904
CEC (meq per 100 g soil)	11.3 (0.3)	10.3 (0.2)	0.021
B. May rotation year 1			
Moisture (g water g^{-1} soil)	0.184 (0.004)	0.128 (0.002)	<0.001
$\log_{10}$ matric potential (−kPa)	2.19 (0.07)	3.22 (0.08)	<0.001
Labile C (mg kg^{-1} soil)	372 (7)	406 (9)	0.006
pH	7.08 (0.04)	6.96 (0.02)	0.027
P_{av} (mg kg^{-1} soil)	50.6 (2.0)	40.2 (1.5)	<0.001
K (mg kg^{-1} soil)	178 (7)	138 (5)	<0.001
Mg (mg kg^{-1} soil)	173 (4)	185 (5)	0.076
Ca (mg kg^{-1} soil)	1520 (50)	1680 (60)	0.045
CEC (meq per 100 g soil)	9.5 (0.3)	10.5 (0.3)	0.021
SOM (% of soil mass)	2.29 (0.03)	2.34 (0.05)	0.427

CEC, cation-exchange capacity; SOM, soil organic matter.

F is the gravimetric water content of the filter paper[71]. Gravimetric soil moisture was quantified as mass loss on drying at 45°C for 72 h divided by dry soil mass.

To determine concentrations of P_{av}, K, magnesium (Mg), calcium (Ca), Zn and Cu, soil was extracted with a Mehlich 3 solution[72,73], and extractant filtrate was subsequently analyzed with inductively coupled plasma spectrometry at the Agricultural Analytical Services Laboratory (AASL) of The Pennsylvania State University (University Park, PA, USA). CEC was determined by summation of K, Mg, Ca and exchangeable acidity[74]. Estimation of SOM followed the AASL protocol. Mass loss on ignition (LOI) was first determined by igniting soil at 360°C for 2 h, and a regression equation was then used to convert LOI to SOM. The regression equation relates LOI to independent estimates of SOM, which are determined by a Walkley–Black procedure that oxidizes organic C with potassium dichromate ($K_2Cr_2O_7$) in an acidic solution[75,76]. Conductivity and pH were determined with appropriate probes inserted into the supernatant of slurries (1 soil:2 deionized water for conductivity, 1:1 for pH) that had been shaken and centrifuged.

Data analyses

Data analyses considered soil conditions before, throughout and at the end of the 3-year experiment. To describe initial conditions, we used multivariate analysis of variance (MANOVA) to compare Starts 1 and 2 with respect to soil attributes observed before our experiment (autumn of year 0) and at its beginning (May year 1). Data were next analyzed with repeated-measures ANOVA (rmANOVA) to determine the interactive effects of tillage, cover crop and start on soil attributes throughout the 3-year period. Between-subjects effects tested for treatment effects (with statistical power dictated by the number of plots), whereas within-subjects effects tested whether any treatment effects varied through time (with statistical power dictated by the total number of observations). A between-subjects test is analogous to determining whether the temporal average in a repeatedly observed response variable (e.g., labile C) differs between two treatment levels (e.g., RT versus FT). A between-subjects test might thus fail to detect responses that only emerge in the final year (particularly responses to tillage, which had no RT–FT contrast until after year 1). Therefore, to assess the final outcome of the experiment, we used ANOVA to analyze treatment effects on soil observations made on single dates in the third rotation year.

To test the hypothesis that labile C was more likely to accumulate under RT than under FT (and to quantify any accumulation rates), we used multiple linear regression to model labile C as an interactive function of tillage and time (time quantified as day number of experiment, equal to 0 on January 1 of rotation year 1). We predict a significant tillage × time interaction, with a more positive regression slope for RT than for FT. This analysis was conducted separately for each start, owing to the disparate behavior of the two starts in the rmANOVA (see Results section).

We used forward stepwise discriminant analysis to determine whether the eight combinations of tillage, cover crop and start could be discriminated by soil variables. This analysis tests whether different farming systems produce different multivariate soil environments. Soil variables available for input included gravimetric soil moisture, matric potential, labile C, SOM, P_{av}, Ca, Mg, K, pH and conductivity; inclusion of a variable required an

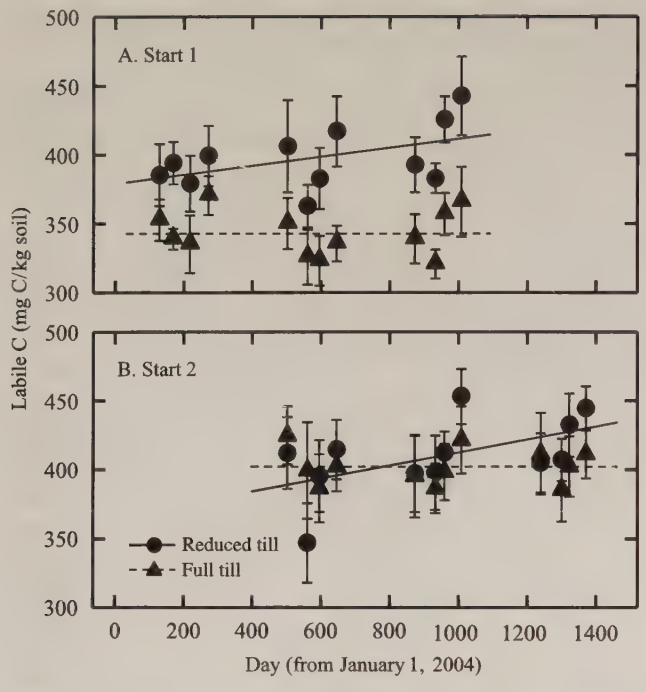

Figure 1. Means and 95% confidence intervals (error bars) of labile C in Start 1 (panel A) and Start 2 (panel B) for each tillage treatment on each day of observation. In each start, regression slopes significantly differ from zero under RT but not under FT (see Table 3).

F-to-enter = 3. This analysis used data from May (or from June–July for conductivity) and was conducted separately for each rotation year.

Results

Initial conditions—difference between starts

The two starts exhibited different initial conditions. In autumn of rotation year 0, acidity, P_{av}, K and CEC were greater in Start 1; Mg was greater in Start 2; and Ca did not differ between starts (Table 2). In May of rotation year 1, gravimetric moisture, P_{av} and K were greater in Start 1; matric potential, labile C, acidity, Mg, Ca and CEC were greater in Start 2; and SOM did not differ between starts.

Labile C

Under RT, labile C increased in the first start by 32.7 μg C kg^{-1} dry soil per day, and increased in the second start by 46.9 μg C kg^{-1} dry soil per day (Fig. 1, Table 3). Thus, with RT used for 3 years, labile C increased 47.8 and 68.5 mg kg^{-1} soil in Starts 1 and 2, respectively, equivalent to 12.7 and 19.0% increases above initial labile C. By contrast, labile C did not change through time under FT (Table 3). By the end of the experiment (October of year 3), labile C was 14.3% higher under RT than under FT (Table 4).

The rmANOVAs support this observation that tillage effects on labile C became more evident through time.

Table 3. Output from the regression model of labile C as an interactive function of time (day of experiment) and tillage. Separate models were fit for each start.

Effect	Coefficient	SE	*P*
A. Start 1			
Y-intercept	381	6	<0.001
Time	0.0327	0.0100	0.001
Tillage	−34.4	9.2	<0.001
Time × tillage	−0.0355	0.0141	0.013
B. Start 2			
Y-intercept	371	8	<0.001
Time	0.0469	0.0130	<0.001
Tillage	19.7	12.0	0.101
Time × tillage	−0.0475	0.0184	0.011

Note: Tillage was an increment parameter (RT = 0, FT = 1). Thus, for RT, labile C (mg C kg^{-1} soil) at day zero is the coefficient for *Y-intercept*, while labile C accumulation rate [mg C (kg soil × day)$^{-1}$] is the coefficient for *time*. For FT, labile C at day zero is the sum of the *Y-intercept* and *tillage* coefficients, while the labile C accumulation rate is the sum of the *time* and *time* × *tillage* coefficients. Day zero is January 1, 2004 for Start 1 and January 1, 2005 for Start 2. The significant *time* × *tillage* coefficient means that the FT treatment has a different slope (labile C accumulation rate) than does the RT treatment. Since RT and FT have different slopes, the significance of the *tillage* coefficient (the RT–FT difference on day zero) depends entirely on which day is arbitrarily chosen as 'day zero'. The ANOVA (Table 4) and rmANOVA (Table 5) models should be referred to for tests of a first-order tillage effect.

When data are aggregated across the 3-year trial, labile C was greater under RT than under FT in Start 1, but was similar between RT and FT in Start 2 (significant between-subjects start × tillage interaction; Table 5). Taking averages across time hides important trends, however. Labile C increased through time under RT but not under FT (significant within-subjects tillage effect), and was consequently greater under RT than under FT by the end of the experiment in both starts. Labile C did not respond to the main effect of cover crop or to its interactions with start and tillage, either across repeated-measures (Table 5) or in analyses of data from single time points in the final rotation year (ANOVA $P>0.1$).

SOM and nutrients

We analyzed several other soil attributes to provide a fuller measure of soil response to field management. Many of them were elevated under RT versus FT by the third rotation year in at least one of the starts or cover crop treatments (Table 4). Yet, because these tillage effects took time to develop, they were not evident when data were aggregated across the 3-year experiment (insignificant between-subjects effects in rmANOVA models). Rather than show tables of rmANOVA model output, therefore, the few significant effects are reported in the text below.

SOM dynamics were affected by tillage in Start 1, but not in Start 2. In Start 1, SOM rose monotonically from years 1 to 3 under RT, but remained flat under FT,

Table 4. Means (and standard errors) of soil attributes compared between RT and FT in rotation year 3. The table lists variables that demonstrate a significant response to tillage by the third rotation year, and indicates the start and cover crop combination in which the tillage effect was significant.

Variable	Reduced tillage mean (SE)	Full tillage mean (SE)	Cover crop and start data group
A. May of rotation year 3			
Labile C (mg kg^{-1} soil)	395.3 (7.2)	341.6 (7.3)	Start 1
Ca (mg kg^{-1} soil)	1488 (53)	1329 (31)	Timothy cover
K (mg kg^{-1} soil)	238.2 (8.4)	164.7 (7.2)	Rye cover in start 1
Mg (mg kg^{-1} soil)	197.5 (3.7)	169.7 (5.8)	Start 1
Mg (mg kg^{-1} soil)	201.1 (10.1)	169.4 (6.9)	Timothy cover in Start 2
Moisture (g water/g soil)	0.210 (0.002)	0.200 (0.002)	Start 1
pH	6.96 (0.03)	6.85 (0.03)	Full dataset
SOM (% of soil mass)	2.67 (0.09)	2.32 (0.09)	Start 1
Zn (mg kg^{-1} soil)	2.20 (0.13)	1.53 (0.07)	Start 1
B. October of rotation year 3			
Labile C (mg kg^{-1} soil)	438.7 (7.9)	383.9 (9.2)	Full dataset
Conductivity ($\mu S\,cm^{-1}$)	108.9 (8.3)	80.9 (4)	Full dataset
Moisture (g water g^{-1} soil)	0.191 (0.010)	0.185 (0.010)	Full dataset
pH	7.22 (0.05)	6.95 (0.05)	Start 1
pH	7.22 (0.05)	6.95 (0.04)	Timothy cover

Table 5. Repeated measures analyses of labile C (mg C kg^{-1} dry soil) as an interactive function of start, tillage, and cover crop.

	Between subjects			Within subjects		
Source	**SS**	***F*-ratio**	***P***	**SS**	***F*-ratio**	***P***
Start × tillage × cover crop	1289	0.15	0.701	2301	0.52	0.891
Tillage × cover crop	2940	0.36	0.556	5046	1.16	0.316
Start × cover crop	1490	0.18	0.675	4626	1.06	0.392
Start × tillage	52986	6.41	0.018	11,142	2.56	0.004
Cover crop	153	0.02	0.899	5182	1.12	0.346
Tillage	92,928	9.86	0.004	26,140	5.64	<0.001
Start	42,588	4.52	0.043	23,304	5.03	<0.001
Time				86,584	14.56	<0.001

Note: For each source, residual degrees of freedom equal 1 in the between-subjects analyses and equals 11 in the within-subjects analyses. *F*-ratios were calculated using partial (type two) sum of squares. Sample size = 32 experimental field plots, with each plot sampled 12 times (four times per year over three consecutive rotation years).

approximating labile C dynamics (Fig. 2). In Start 2, however, SOM in both tillage treatments rose from rotation years 1 to 2 but fell again by year 3. This sensitivity of SOM to tillage in Start 1, but not in Start 2, was evident across repeated measures (between-subjects start × tillage interaction $P = 0.006$), and in May of the final rotation year (Table 4). Cover crop had no effect on SOM across repeated measures or on SOM concentrations in the final rotation year.

By the third year of the trial, base cations were greater under RT than under FT in many combinations of start and cover crop (Table 4). Mg was about 18% greater under RT than under FT in Start 1 and in the timothy cover crop treatment in Start 2. Ca was 12% greater under RT than under FT in the timothy cover crop treatment, but did not differ between tillage treatments in the rye cover crop treatment. Finally, K was 45% greater under RT than under FT in the rye cover crop treatment in Start 1, but did not differ between tillage treatments for the other combinations of cover crop and start. Differences between RT and FT were less evident with base cation data aggregated across repeated measures. Soil K was greater in Start 1 than in Start 2 (between-subjects start effect $P < 0.001$). Additionally, K was greater under RT than under FT in Start 1 (reduced-till K = 186.6 ± 4.1 mg kg^{-1} soil; full-till K = 165.6 ± 6.4; ANOVA $F_{1,14} = 7.69$, $P = 0.015$, $n = 16$ plots), but did not differ between RT and FT in Start 2 ($P = 0.7$). Otherwise, no base cation responded to the tillage or cover crop treatments with data aggregated across repeated measures (between-subjects tillage and cover crop effects $P > 0.05$).

Soil P_{av} did not respond to tillage, cover crop or their interactions, either when viewed across repeated measures (between-subjects $P > 0.05$) or when analyzed on single-time points in rotation year 3. However, P_{av} was higher in Start 1 (mean ± SE = 50.3 ± 1.3 mg P_{av} kg^{-1} soil) than

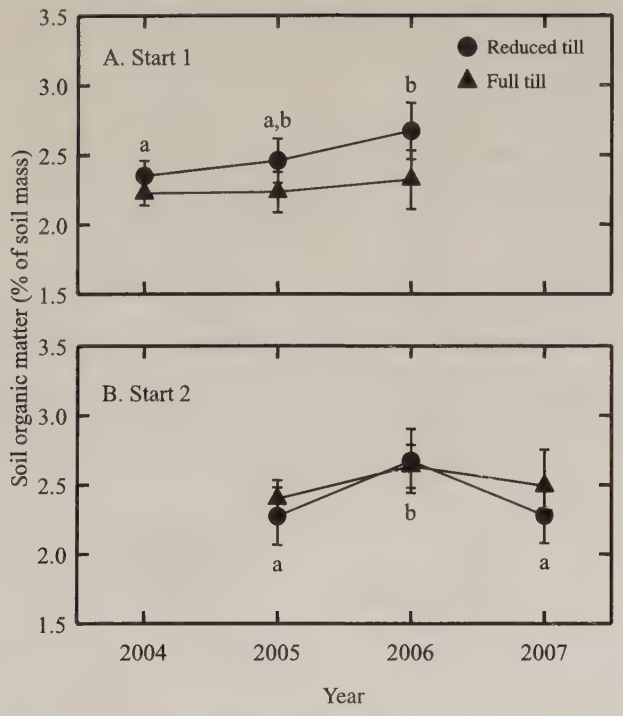

Figure 2. Means and 95% confidence intervals (error bars) of SOM in Start 1 (panel A) and Start 2 (panel B), in May of the indicated years. Letters denote statistical comparisons among years for the RT treatment (circles). There were no significant differences among years for the FT treatment (triangles). A comparison between RT and FT is reported in the text.

in Start 2 (37.8 ± 1.2 mg P_{av} kg^{-1} soil; between-subjects start effect $P < 0.001$), consistent with the different initial conditions (Table 2).

Soil conductivity, pH, bulk density and water

Soil conductivity and pH were both greater under RT than under FT by the end of the trial (Table 4). In both May and October of rotation year 3, pH was 0.1–0.2 pH units greater (roughly half to three-fourths as much soluble acidity) under RT than under FT in all treatment combinations, except in the rye cover crop treatment in Start 2 in October. Conductivity was 34.6% higher under RT than under FT by October of year 3. These responses to tillage were not evident until the end of the trial, however. In the repeated measures analyses, tillage and cover did not have significant main or interactive effects on conductivity and pH (between-subjects $P > 0.05$). Soil bulk density was greater in Start 1 than in Start 2 (1.51 versus 1.45 g dry soil cm^{-3}; SE = 0.01; $P = 0.021$), but did not respond to tillage or cover crop in any combination of start, year and depth.

Soil moisture conditions differed little between tillage treatments by the end of the trial. Across repeated measures, mean matric potential fluctuated from −79 to −4199 kPa (within-subjects time $P < 0.001$), but showed no directional or seasonal trend. Where soil matric potential responded to treatments, it was generally stronger in Start 2 than in Start 1 (between-subjects start $P < 0.001$), and where timothy rather than rye served as the first-year cover crop (between-subjects cover crop $P < 0.001$). These treatment effects were not evident at most time points considered individually, however, as start and cover crop exhibited significant within-subjects effects ($P < 0.05$). Gravimetric soil moisture generally mirrored matric potential. It varied through time from 118 to 221 mg water per gram dry soil (within-subjects time $P < 0.001$), yet showed no directional trends. Moisture was generally greater in Start 1 than in Start 2 (between-subjects start $P < 0.001$), and was greater in the rye than in the timothy rotation (between-subjects cover crop $P < 0.001$). Again, such patterns were not evident at most time points, as start and cover exhibited significant within-subjects effects ($P < 0.01$). By the final time point in the experiment, moisture was 3% greater under RT than under FT (Table 4). Lastly, in analyses of single time points in rotation year 3, no soil attributes exhibited a response to the main effect of the cover crop.

Table 6. Soil attributes included in the forward stepwise analysis, listed in order of importance. The hypothesis that these soil attributes could discriminate treatment groups (start/tillage/cover crop combinations) was supported, as Wilks' lamba, Pillai's trace, and the Lawley–Hotelling trace all had $P < 0.001$ in each rotation year.

Rotation year	Discriminating variable	Wilks' lambda	*F*
Year 1	Conductivity	0.0375	87.9
	Matric potential	0.0171	21.8
Year 2	Moisture	0.0763	41.5
	Conductivity	0.0248	17.6
Year 3	Moisture	0.1954	14.1
	Labile C	0.0546	10.8
	K	0.0242	8.0

Discriminating farming systems

In each rotation year, the discriminant analysis identified two or three soil variables that discriminated the eight start/tillage/cover crop combinations (Table 6). The canonical variables (factors) created by these soil attributes were 100% successful in classifying plots according to their start. Within a start, however, these factors were poor at classifying plots according to their tillage/cover crop treatment. In rotation years 1 and 3, only 12 of the 32 plots were classified in their correct tillage/cover crop treatment; in rotation year 2, only 13 of the 32 plots were classified correctly.

The starts were clearly distinguished from one another along the first factor (Fig. 3). In contrast, the cover crop and tillage treatments were not distinguished. This first factor was vastly more important than the second factor; the eigenvalues for factor 1 were 33, 17 and 11 in rotation years 1–3, respectively, compared with much smaller eigenvalues for factor 2 of 0.7, 1.3 and 1.4 in the same years. Moreover,

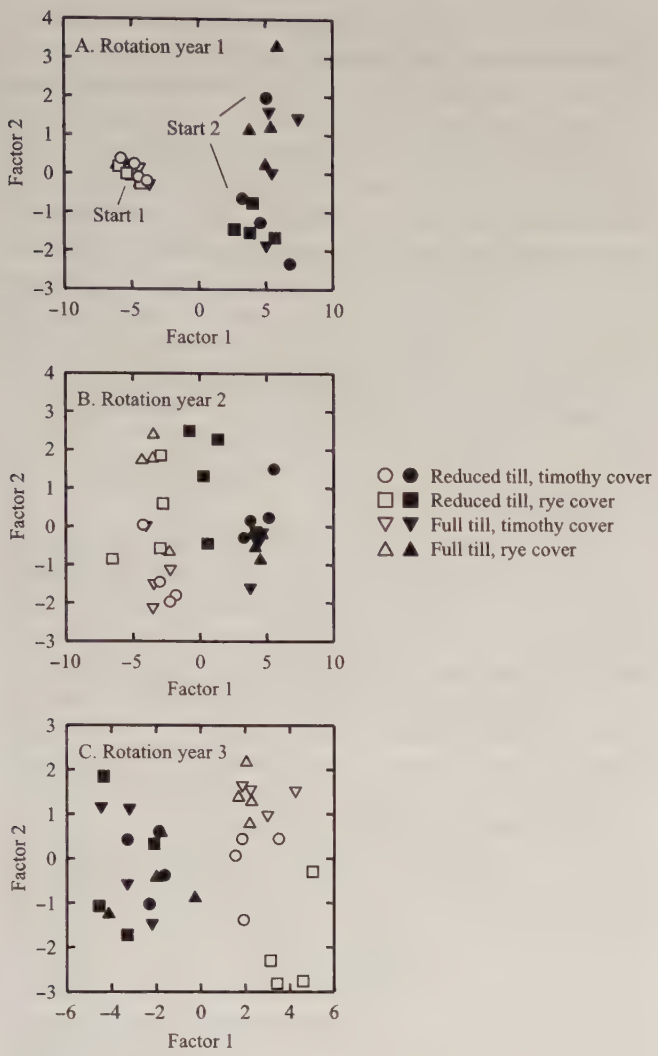

Figure 3. Factor scores from discriminant analysis of eight treatment groups (two starts × two tillage levels × two cover crops), discriminated with forward stepwise inclusion of soil attributes observed at the beginning of three consecutive rotation years. A separate discriminant analysis was conducted for each year. Three canonical variables were created in the analysis of year-3 data; only the first two are displayed here. Note that a given factor is not comparable among years, as it comprises different variables in different years.

the proportion of among-group dispersion for which factor 1 was responsible was 98, 93 and 86% for rotation years 1–3, respectively. The F statistics to test the equality of group means were much larger when comparing across starts than among treatments within a start. For example, in the first rotation year, the full till/rye plots of Start 1 looked much different from their counterparts in Start 2 ($F_{2,23} = 104$) than they did from other till/cover combinations in Start 1 ($F_{2,23} < 1$).

Discussion

Soil response to tillage

Our results indicate that growers transitioning to organic production may be able to build soil quality while pursuing limited tillage activities. During this 3-year experiment, labile soil C increased ~15% under RT with chisel plowing. This accumulation of labile C likely provides a host of agronomic and ecological benefits. Soil labile C regulates N availability to plants, limits N leaching loss by acting as a substrate for heterotrophic metabolism and N immobilization[77], and according to mass balance represents reduced net carbon emission from the biologically active C pool. Although Start 2 did not exhibit higher labile C under RT across all time points (rmANOVA results), this outcome resulted from low labile C in the RT plots on one date in rotation year 1 (Fig. 1B), before the tillage treatments were imposed. By the end of year 3, labile C was greater under RT than under FT for both starts. It seems encouraging that full inversion tillage did not further deplete labile C, because soil inversion was a successful weed control tactic[68]. Yet, simply maintaining a dynamic equilibrium at 350–400 mg labile C per kg soil might be viewed as insufficient, as other Pennsylvania farms exhibit >1000 mg labile C per kg soil when quantified using the same laboratory protocol[57]. Labile C probably failed to accumulate under FT because soil inversion permits the loss of organic C by destroying soil macroaggregates[62] and stimulating respiration[61].

SOM concentrations corroborate the trends in labile C (accumulation in RT but not FT) in Start 1, but tillage had no effect on SOM in Start 2. The inconsistency between starts may have derived from two methodological differences. One, the Start 2 field experienced 2 years of cover cropping prior to implementing the RT versus FT contrast, so it may have been relatively insensitive to tillage during rotation years 2 and 3. Two, the plots in Start 2 were tilled more often than the plots in Start 1 were (Table 1), and this extra cultivation may have inhibited SOM accumulation. Both of these explanations, while plausible, must be viewed with some skepticism because they are inconsistent with the fact that tillage had strong effects on labile C in both starts. Rather, a longer experiment, or more frequent sampling with observations at the end of growing seasons (SOM was only observed each May), may have revealed a more pronounced effect of tillage on SOM. Furthermore, because most SOM is recalcitrant (labile C < 2% of SOM), tillage may affect SOM less than it affects labile C.

The relatively low levels of pH, conductivity and several Mehlich 3-extractable elements (K, Mg, Ca and Zn) under FT by the third rotation year are consistent with previous findings[63]. Tillage may reduce available binding sites or stimulate ion exchange that replaces base cations with other cations, such as H^+, consistent with the lower pH under FT. Gravimetric soil moisture may be slightly lower under FT than under RT owing to a reduction in pore space and loss of water retention capacity[78]. Increases in any of these soil quality metrics would be evident both per unit soil mass and per unit area of field because bulk density was not affected by tillage.

Soil response to cover crop

Owing to its potential for greater biomass production, we expected that the rotation initiating with a sod-forming perennial cover crop mixture (timothy, oat and red clover) would have greater SOM and labile C than the rotation initiating with annual grain cover crops (rye followed by hairy vetch). Yield data contravened these expectations, however, as timothy harvest was 115% of rye harvest in Start 1, but only 30% of rye harvest in Start 2[68]. Correspondingly, no soil chemical attributes differed between the two initial cover crop treatments. Hydrological attributes (gravimetric moisture and matric potential) did differ between cover crop treatments, but only at a limited subset of observation times. In the final-year analyses, no soil attributes differed between the cover crop treatments. This lack of differences by the end of the experiment may reflect that the crop rotations were identical in years 2 and 3, and is consistent with our prediction that the effects of the first year cover crop would be less or not evident late in the experiment. Research in a California vineyard similarly observed that different cover crop systems did not have disparate effects on measured soil properties, despite having strong effects on weed productivity and diversity[79].

Start effect—role of initial conditions and weather

Start had a pervasive influence in our experiment. Between the two starts, soil attributes often had different mean values, had different temporal dynamics or exhibited inconsistent responses to tillage (with Start 1 but not Start 2 showing a tillage effect). This influence of start may result from differences between the starts in initial soil conditions (Table 2), itself perhaps due to the extra cover crop year in Start 2. The influence of start may also result from differences between starts in precipitation regime. Owing to interannual variability in summer precipitation, the cover crop, soybean and maize years were, respectively, wet, dry and normal in Start 1, while they were dry, normal and normal in Start 2.

We are not able to determine why the Start 1 and Start 2 fields had different initial conditions, and it is beyond our scope to determine whether different initial conditions or precipitation regimes truly did cause different behaviors between the starts during the ensuing 3 years. Nevertheless, our results do raise the consideration that initial conditions and weather may render the outcomes of management treatments unpredictable. Our duplicate experiments were conducted on adjacent fields, were temporally offset by only 1 year, and were conducted on fields that had previously been consolidated under homogeneous management. Thus, the 'different' contexts of our two experiments were actually quite similar, and yet we still observed inconsistent tillage effects on the soil attributes reported here, and on weed, soil biota, yield and profitability metrics reported by others[67–69]. This cautionary note is important, because scientists and practitioners may typically wish to generalize across much more disparate contexts.

Interestingly, the starts may have been converging while the treatments were slowly diverging. The discriminant analysis indicated that the eigenvalue for factor 1 (the 'start-discriminating' factor) declined with time, as did the proportion of among-group dispersion for which factor 1 was responsible. And, the average F-statistic to compare the same tillage/cover crop strategy between starts declined through time (95, 47 and 22 in rotation years 1, 2 and 3, respectively). Within at least Start 1, meanwhile, the plots had begun to separate into tillage groups by year 3 (note open triangles in Fig. 3C).

Agroecosystem management implications

Our results demonstrate that reduced tillage results in soils with greater labile C (Fig. 1) and some other soil quality metrics (Table 4) that are representative of yield and nutrient cycling. These benefits of reduced tillage for soil quality on transitioning farms need to be placed into a broader agroecosystem perspective, and here we briefly summarize companion research that considers tillage effects on weed pressure, biological control agents, crop yield and profitability in our experiment.

Reduced and full tillage performed similarly at suppressing emergence of annual weed seedlings from experimentally sown seeds[69]. The density of weeds emerging from the existing seed bank, however, was 82% greater under RT than under FT during the second-year soybean phase of Start 1, and about 244% greater under RT than under FT during the third-year maize phase of both starts[68]. Another chisel-plowed, organic feed-grain system in our Mid-Atlantic region similarly experienced high weed emergence[29]. Tillage may also influence insect pests through direct effects on soil-dwelling biological control agents. The entomopathogenic fungus *Metarhizium anisopliae* is one such control agent that was prevalent in our plots. Final *M. anisopliae* counts at the end of year 3 were higher under FT than under RT in Start 1, possibly owing to preferentially lower moisture or higher spore mobility in disturbed soil, but counts did not differ between tillage treatments in Start 2[67].

While RT in our experiment was superior for promoting soil quality and inferior for controlling weeds and conserving a biological control agent, these outcomes do not collectively translate into substantial effects on yield and profitability. Soybean yields in both starts, and maize yields in Start 2, were not affected by tillage[68]. Tillage had a muted effect, at most, on profitability[68]. Net returns were significantly higher under RT for soybeans and under FT for maize in Start 1. The 3-year cumulative net returns were not significantly affected by tillage in either start. Of the eight farming systems (two starts × two tillage strategies × two cover crop regimes), the 3-year cumulative net returns were positive in five. The three negative returns were associated with rye cover crop, not tillage strategy.

These returns did not include organic price premiums, and could have been universally higher and positive with the use of manure rather than expensive compost fertilizer[68]. Collectively, this experiment indicates that with wise use of cover crops and cost-effective fertilizer, organically managed feed-grain farms in the Mid-Atlantic can use RT to build soil quality (primarily labile C and base cations) during the transition period and still remain profitable over these three years.

Acknowledgements. We thank Christina Mullen, Cathy Nardozzo and David J. Sandy for technical assistance, and Richard G. Smith and Tara Pisani Gareau for helpful comments on an earlier version of the manuscript. Funding was provided by the Organic Agriculture Research Initiative of the USDA (Grant no. 03-4619).

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Renewable Agriculture and Food Systems: 26(4); 354–367 doi:10.1017/S1742170511000251

Contribution of farmers' experiments and innovations to Cuba's agricultural innovation system

Friedrich Leitgeb[1,*], Fernando R. Funes-Monzote[2], Susanne Kummer[1] and Christian R. Vogl[1]

[1]Working Group: Knowledge Systems and Innovations, Division of Organic Farming, Department of Sustainable Agriculture Systems, University of Natural Resources and Life Sciences (BOKU), Vienna, Austria.
[2]Estación Experimental Indio Hatuey, Central España Republicana, Universidad de Matanzas, Perico, Matanzas, Cuba.
*Corresponding author: friedrich.leitgeb@boku.ac.at

Accepted 30 May 2011; First published online 13 July 2011 **Research Paper**

Abstract

Innovations are the driving force for agricultural development under present diverse situations of uncertainty. The innovation system perspective acknowledges the contributions made by all stakeholders involved in knowledge development, dissemination and appropriation. According to the specific agricultural production system, farmers adopt innovations, modify them or innovate on their own. This paper examines the role of farmers' experiments and innovations in Cuba's agricultural innovation system (AIS), identifies knowledge exchange encounters and describes some strategies implemented to institutionalize farmers' experiments and innovations. The research methods comprised 34 semi-structured interviews with agricultural experts from the science, administration and advisory system, and 31 free list questionnaires to assess the institutional influence on farmers' experiments and innovations. In addition, three case studies of outstanding farmers' experiments are presented. The results suggest that the government's commitment to social participation in knowledge development provides the basic prerequisite for an effective integration of farmers' experiments and innovation in Cuba. The historically conditioned vertical structure of knowledge development and dissemination is gradually changing toward more horizontal procedures. The dynamic exchange of ideas at all kinds of interactive meetings, such as workshops or farmers' field schools, have favored farmer to farmer learning as well as knowledge sharing with research, academic and extension officials. This multi-stakeholders' approach contributes to institutionalize farmers' knowledge. Farmers' experiments and innovations play a major role in improving farm management and thereby can contribute to build resilience at the farming system level as well as for the national agricultural system.

Key words: innovation, farmers' experiments, knowledge system, agricultural innovation system, participation

Introduction

The worldwide food crisis[1], food insecurity[2], expected drastic impacts of already ongoing climate change on agricultural production[3] and immense migration phenomena of former rural people, including farmers, to cities[4] have brought politicians, scientists and the civil society to rethink conventional agricultural practice. The International Assessment of Agricultural Knowledge, Science and Technology for Development (IAASTD) has demanded an urgent need for change to improve the efficiency and sustainability of food production[5]. Global change calls for strategies to support the innovative capacity of rural people in improving agricultural production based on their traditional ecological knowledge[6].

Innovation, in general, is widely accepted to be a driving force for development. Increasingly, scientists and extension agents recognize the key role of innovative farmers and acknowledge their experiments and innovations for agricultural development[7–10] and for farming systems' resilience[11,12]. Farmers hold a crucial position because they test the feasibility of agricultural innovations and adapt them, if necessary, until they fit to local conditions. However, the capacity of farmers to develop valuable innovations on their own is still frequently underestimated and their contribution to formal research and development

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agendas often remains neglected. Nevertheless, farmers' experiments and innovations have been part of agriculture over thousands of years and were driving forces for development[9,13,14]. Nowadays, the innovative capacity of farmers, research activities of scientists and other stakeholders engaged in rural development increasingly merge and lead to participatory research and development approaches. The most common attitude of scientists and extensionists toward traditional knowledge and technology transfer is gradually shifting to more participatory approaches. Such participatory views typically improve efficiency and applicability of research outcomes[15–22]. However, research and development in agriculture are embedded in a complex framework of underlying conditions (e.g., political, administrative or financial) that directly influence the nature of farmers' experiments and innovations[23].

Cuba's economy and society face special circumstances because of its geographic location and history. After the Revolution in 1959, the Cuban government favored intensive production systems using a high proportion of foreign inputs and top-down knowledge and technology transfer[24]. Trade relations with the former socialist countries in Eastern Europe that were established in the early 1960s and the United States trade embargo shaped the basic conditions for research and development in agriculture. The collapse of the socialist block in 1989 led to major changes that had a drastic impact on the economy and society[25]. Resource scarcity turned into an ever-present constraint for Cuba's agriculture and triggered the shift toward more sustainable ways of production, including the establishment of local food systems and a more ecological approach in agriculture[26].

Cuba's long history with public participation in innovation development, the current innovation policy and the national legislation shape the boundaries of the agricultural innovation system (AIS). National legislation for agriculture regulates the distribution of farm land, prices, the establishment of trade relationships to foreign suppliers or costumers, input supply and the commercialization of agricultural commodities. As a result, the agricultural sector is relatively closed and intensively controlled. This makes farmers' experiments and innovations in Cuba and their potential within the AIS unique to study.

We hypothesize that farmers' endogenous potential to experiment and innovate constitutes a valuable contribution to knowledge and technology development. Agricultural policy, scientific research and the formal advisory system can strengthen farmers' experiments and innovations if they do consider them as valuable elements in the domestic AIS. We will not be able to prove that farmers' experiments and innovations are crucial to prepare agriculture for global change, but we do claim that they play a significant role in Cuba's AIS and are probably often ignored in many other parts of the world.

In this paper, we examine the role of Cuban farmers in knowledge and technology development, and their contribution to and integration into the AIS. After briefly introducing the key concepts and providing a conceptual framework for the study, we draw attention to Cuban farmers' knowledge and information system. In addition, we present evidence of farmers' experiments and innovations in Cuba and their institutional linkage. Finally, we describe strategies to institutionalize farmers' experiments and innovation.

Methods

Field research in Cuba was conducted following the methodological framework of a research project about organic farmers' experiments. The project was carried out in Austria, Cuba and Israel by three PhD students. The study was aimed at generating empirical knowledge on the processes whereby organic farmers experiment and innovate, and how they generate new knowledge. In this paper, we concentrate on selected results from that study. Data collection in Cuba was carried out in 2007 and 2008 for 5 months each year. During this period, 34 expert interviews, based on a semi-structured interview guide, were conducted with representatives of research institutions, agricultural administration, the advisory system, farmers' organizations and international development agencies[27]. The selection of the interviewees was based on purposeful sampling combined with snowball sampling[28]. Recommendations of local counterparts from research institutes helped in selecting appropriate interviewees. The selection criteria included their expertise in the fields of farmers' experiments and innovations, agricultural extension and organic farming. A semi-structured interview was applied to cover topics such as the institutions' mission and objectives, the institutions' information and knowledge systems, the interviewees' perception of farmers' experiments and innovations, sustainable agriculture and organic farming in Cuba. In addition, 31 free lists[29] were collected to assess the institutional influence on farmers' experiments and innovations.

The interviews lasted between 45 min and 2 h, depending on time availability of the respondent and the willingness to share information. For analysis of secondary data, newspaper and magazine articles, brochures, proceedings of events and other relevant media publications were revised. Although expert interviews were an integral part of data collection, field research was primarily focused on farmer interviews to study the farmers' perception of experimenting and innovating[30]. Thus, a total of 69 semi-structured interviews with farmers were conducted from which three selected examples of farmers' innovations were analyzed for this paper.

Each interview was recorded with a digital voice recorder, transcribed with Express Scribe software, coded and analyzed using the software Atlas.ti. Interview data were revised according to a content analysis approach, based on a combination of deductive and inductive coding. Pre-defined codes and emerging codes were assigned to text chunks with similar content. Codes were organized into code families to obtain thematic categories[28–32]. Working with farmers as key informants permitted additional

insights into farmers' perceptions of their experiments. Participant observation completed the set of methods to gain additional insights into farmers' participation in scientific and semi-scientific conferences, innovation award forums, innovation fairs, workshops, seminars and farmers' meetings. During all events, selected relevant phases were digitally recorded and protocols were elaborated and analyzed in the same way as described for the interviews[29].

Definition of AIS

There are different commonly used definitions of 'innovation', depending on the discipline involved. The innovation system approach defines an innovation as 'doing something new by using existing or novel knowledge in new ways'[33]. In the agricultural context and at farm level, an innovation is considered 'something new that started within the lifetime of a farmer'[34]. This means that an innovation is new for the individual but can already be known by others, while an invention is an absolutely new idea or technology that has been discovered or created for the first time[35].

The innovation system approach reflects the interactive and social character of an innovation and provides an understanding of the dynamic processes involved. An innovation system includes stakeholders at governmental and non-governmental levels, their interactions and contributions to the development, the dissemination and application of knowledge and/or technology. AIS stakeholders may include multinational and national agribusinesses, as well as small-, medium- and large-sized ones, individual stakeholders, cooperatives, farmers' organizations or other community-based groups at the market level, national and international research institutes, extension services, government marketing agencies, higher-education institutions and non-governmental organizations (NGOs). All of them interact on the basis of market and non-market relations[36].

The smallest AIS units are individual stakeholders, such as farmers or farm workers, and stakeholder groups, such as farm households or rural communities[37]. These units either develop or adopt innovations and knowledge and eventually put them into practice. Consequently, they determine whether an innovation is developed enough to suit local conditions or whether it requires further adaptation to such conditions[38].

Knowledge and its development, dissemination and appropriation play a key role in innovation systems. Knowledge development is a process of constant feedback between empirical observation and interpretation of the observed[39]. However, knowledge is more than the simple accumulation of information. It is characterized by its applicability and usability[40]. It can be classified into scientific and local knowledge. Scientific knowledge is accumulated by systematic study, is codified and explicit. Local knowledge, by contrast, is generated over time and consists of accumulated experiences, practices and beliefs. It evolves from adaptive processes, is implicit and passed on orally or by shared practical experiences[41]. Knowledge, in general, can be embodied in a technology, a commodity or a service, or it can be detached and appear in a method or practice[42]. Every type of knowledge is specific to a certain production sector; hence, the agricultural sector relies on a site-specific knowledge base. Knowledge exchange encounters[43] are important to increase the availability of information and to provide learning opportunities for the stakeholders involved in innovation processes. Innovation and knowledge are complementary concepts since the development of an innovation leads to the development of new knowledge. Vice versa, the appropriation of new knowledge potentially leads to an innovation. Therefore, those farmers' activities that eventually lead to innovations and/or to the development of new knowledge can be labeled as 'farmers' experiments'.

The term 'farmers' experiments' means the 'research conducted by farmers for the discovery or generation of information'[44]. Farmers' experiments usually aim at testing the validity of a hypothesis or trying something new. Throughout the long history of agriculture, farmers have developed lots of technologies and built up specific knowledge bases for their respective local environments[45]. Thus, informal research by farmers can be a major source of agricultural innovations[46–49].

Results

General description of Cuban farmers' knowledge and information system

Knowledge and information are basic AIS elements. Personal communication and individual interaction facilitate learning processes, adaptation and development of new knowledge. Knowledge develops either from external information sources or from own activities that include a learning component, or both. Cuban farmers derive external information from other farmers, extension agents and scientists as well as from the media. Communication with other farmers is a valuable source of information because it is usually based on similar communication and livelihood patterns which result in trust and mutual understanding.

Scientific institutions, represented through their staff members, spend considerable time, effort and resources to transfer technologies; however, farmers often have to adapt and reformulate them to their own local conditions. Knowledge exchange between scientists and practitioners is crucial to accept the challenge of agricultural production under limited economic conditions.

Formal extension services. Extension agents of the Ministry of Agriculture (*Ministerio de la Agricultura*, MINAGRI) at municipal level, associated with the state-owned agricultural enterprises and local staff members of the National Small Farmers' Association (*Asociación Nacional de Agricultores Pequeños*, ANAP) form the more active bodies that provide information and technical assistance for farmers. Other important sources for agricultural advice at local level are the 73 territorial stations belonging to the National Center for Plant Health

Table 1. Distribution and number of ANAP members[50,51].

Type of cooperative production	No. of cooperatives	No. of members	% of total workforce in agriculture[1]	% of total cultivated land[2]
CPA	1089	62,494	7%	10.2%
CCS	3242	269,380	28%	17.9%
Total	4331	331,874	35%	28.1%

CCS, Cooperatives of Credits and Services (*Cooperativa de Créditos y Servicios*); CPA, Cooperatives of Agricultural Production (*Cooperativa de Producción Agropecuario*).
[1] Total workforce in agriculture, forestry, hunting and fishing: 945,600.
[2] Total cultivated land: 2,988,500 ha.

(*Centro Nacional de Sanidad Vegetal*, CNSV) and the Centers for the Reproduction of Entomophage and Entomopathogens (*Centros de Reproducción de Entomófagos y Entomopatógenos*, CREE), both working in close relationship with the Plant Health Research Institute (*Instituto de Investigaciones de Sanidad Vegetal*, INISAV). INISAV maintains a network of territorial stations and deals with plant protection. Each station employs about ten extension agents in charge of providing services to individual farmers and cooperatives. They make field visits and organize workshops, seminars and courses according to local and national demands. Extension agents make use of audiovisual material such as short videos, computer presentations and leaflets. However, elaboration of written material to inform farmers is limited because plant protection personnel face resource shortages. Thus, oral knowledge prevails in most extension situations.

Each municipality counts on several extension agents who assist individual farmers and cooperatives. In addition, there are research entities distributed all over the country, even in the most remote areas, close to farmers. The topics covered by these institutions can include pest and disease control, seed and soil management and, to a lesser extent, irrigation, processing and marketing.

Although Cuba's agricultural administration is engaged in improving transfer of technology and extension services, delivery efficiency is still a challenge. Potential end-users of agricultural innovations frequently could not properly access useful results from formal and informal channels. Thus, farmers' attempts to adopt innovations are less effective than they could be. This dilemma has been internalized by the Ministry of Science, Technology and the Environment (*Ministerio de Ciencia, Tecnología y Medio Ambiente*, CITMA), which commissioned the Center for Local and Community Development (*Centro de Estudios de Desarrollo Local*, CEDEL) to elaborate an inventory of highlighted innovations and inventions of Cuban research institutions. Also, remarkable inventions of farmers are mentioned in the inventory. This 'Catalog of Technologies for Local Development' aims at increasing awareness of innovations among farmers and extension agents and thereby contributes to the dissemination of new and site-appropriated agricultural knowledge. Structure and language of the catalog are clear and concise and therefore guarantee the utility for potential end-users. However, final implementation of the technologies and methods presented in the catalog will, certainly, strongly depend on the willingness and competence of the local government and agricultural administration. A farmer's role is to assess the applicability and feasibility of the innovations for site-specific conditions.

ANAP is a member of the transnational peasant movement, La Via Campesina, that defends small farmers' rights. ANAP is the most widespread institution for knowledge dissemination among farmers in Cuba. It runs offices in all municipalities, represents farmers' interests before the government and, simultaneously, is the government's vehicle to disseminate relevant information. ANAP represents all farmers belonging either to Cooperatives of Credits and Services (*Cooperativa de Créditos y Servicios*, CCS) or Cooperatives of Agricultural Production (*Cooperativa de Producción Agropecuario*, CPA). The Cooperatives of Credits and Services are associations of farmers who own their farmland or have acquired the land in usufruct. The members of Cooperatives of Agricultural Production collectively own the farmland (Table 1).

Both cooperatives organize a monthly meeting where all members are asked to participate to talk about topics such as cooperative administration, technical issues or agricultural policy. One ANAP representative usually participates in the cooperative meeting to inform farmers about relevant news in agriculture. Thus, information provided by the ANAP reaches every farmer. Its nationwide structure assures an educational and training program that comprises 117 training sites distributed throughout the island and a national center located in the province of Havana.

Farmer-to-farmer extension. An example of horizontal dissemination of knowledge is the Agroecological Farmer-to-Farmer Movement (*Movimiento Agroecológico de Campesino a Campesino*, MACAC), initiated by ANAP in 1997. Each municipal office of ANAP employs a representative who coordinates and supervises all activities related to the movement. The main pillars of the farmer-to-farmer movement in Cuba are those participants who become 'facilitators' and 'promoters'. Facilitators usually have a high education standard, good communication skills, hold broad knowledge in agricultural issues and some of them are agricultural technicians. They often

promote the introduction of agroecological innovations, assist farmers during the experimental stage of adoption, organize workshops and coordinate farm visits. Cooperatives that choose to employ a facilitator pay for the service. However, facilitators are not typical extensionists, since they usually live in rural areas and most of them are farmers themselves. As for promoters, they are farmers themselves and their colleagues admit that they are research minded, enthusiastic experimenters and eloquent communicators. They experiment with promising technologies or practices and search for local solutions for specific challenges. Promoters open their farms for field visits and are willing to share their knowledge with their peers, using the farmer-to-farmer approach.

The movement spread rapidly all over Cuba and is famous even beyond the borders of the country. About 110,000 farmers' families have joined the movement since its implementation and now represent more than one-third of all ANAP members[52]. The success of the farmer-to-farmer methodology reflects ANAP's willingness to support a participatory, dynamic and bottom-up movement with agroecology and farmers' experiments as a basic condition.

In addition to formal extension services of ANAP, the farmer-to-farmer movement provides an organizational framework for the horizontal diffusion of farmers' agroecological experiments and innovations. It plays a key role in facilitating knowledge exchange among farmers, providing agricultural training and education and offering extension services.

Although the ANAP is the leading organization of farmer-to-farmer extension in Cuba, there are other accompanying institutions and organizations, such as the National Institute of Agricultural Science (*Instituto Nacional de Ciencas Agrícolas*, INCA). This research institute has been working since 1999 with farmers, encouraging them to experiment. Local staff members invite farmers to participate in the so-called Center for Local Agricultural Innovation (*Centro Local de Innovación Agropecuaria*, CLIA). Periodically organized encounters for knowledge exchange such as training courses, workshops or seed exchange fairs have been crucial elements for farmer-to-farmer and farmer-to-scientist interaction. Other institutions that offer extension services and encourage knowledge exchange among farmers are the Cuban Association of Agricultural and Forest Technicians (*Asociación Cubana de Técnicos Agrícolas y Forestales de Cuba*, ACTAF) and the Cuban Association of Animal Production (*Asociación Cubana de Producción Animal*, ACPA).

Urban agriculture. Urban agriculture is a special case in the extension service and knowledge exchange system. The government has been supporting urban agriculture since the early 1990s due to its positive contribution in overcoming the economic and food crisis. The National Group for Urban Agriculture (*Grupo Nacional de Agricultura Urbana*, GNAU) was created in 1997 to assure its growth and to strengthen its development. Each municipality runs an office that coordinates the urban agriculture activities, including organization, administration, extension services, etc. Urban agriculture extensionists typically live close to urban gardens and normally share similar knowledge and viewpoints with farmers. Establishing rapport takes place in a natural way and eventually helps improving efficiency of their work.

Mass media. The formal advisory system frequently uses mass media as a cost-effective means to reach a wide range of farmers and, simultaneously, to go easy on available resources. Agriculture-oriented TV programs and news from radio broadcasting or newspapers make information accessible to farmers living in remote areas. Some experimental stations of INISAV even run their own radio programs. In some cases TV or radio programs include reports on farmers' experiments and innovations. A remarkable example of knowledge dissemination using documentaries is the Program for Local Agricultural Innovation (*Programa de Innovación Agropecuaria Local*, PIAL), a development project implemented by INCA.

Training for extension agents. Extension agents play a key role in Cuba's AIS. Despite the lack of an articulated and universal extension service in Cuba, there is considerable social capital and intellectual potential to cover the needs of the agricultural sector. Keeping them up-to-date through further education and capacity building improves the efficiency of knowledge dissemination. ACTAF pursues knowledge exchange by providing training and education to extension agents and other professionals throughout the country. With branch offices in each province and about 23,000 members all over the country, it is one of the most important associations for technicians in the agricultural sector. ACTAF frequently organizes workshops on a cooperative basis, conferences and seminars and publishes books and a magazine on sustainable agriculture and organic farming. Another important organization is ACPA, also with some 20,000 members, which emphasizes knowledge exchange, facilitates access to agricultural information and provides capacity building, education and extension services. Other organizations, such as the Cuban Association for Sugar Cane Technicians (*Asociación Cubana de Técnicos Azucareros*, ATAC), cover a more specialized knowledge domain.

All these initiatives and platforms contribute to increase the farmers' agricultural knowledge pool. However, bureaucracy and top-down mentality are historically caused and are part of many governmental institutions, including research entities and extension services. This situation has changed slightly over the past two decades but occasionally lowers the flexibility and efficiency of extension services. Thus, Cuban farmers' informal communication networks are indispensable channels for knowledge dissemination and exchange.

Farmers' experiments and innovations in Cuba

During the so-called 'special period' (from 1990 to the present time) Cuban farmers have had to become more

innovative to overcome the economic and food crisis. Cuba's government started to support new and sustainable technologies (e.g., biological pest control and organic fertilizer production) and reorganized the agricultural structure (e.g., farm diversification, downsizing of large farms and offering of land in usufruct). Government officials encouraged farmers to experiment with sustainable agriculture practices. Farmers, in turn, had little other choice than experimenting with low-input agriculture. Besides the government and farmer approaches to optimize rural farming, urban dwellers became increasingly engaged in food production and initiated the urban agriculture movement in Cuba. Farmers' experiments and innovations turned out to be an indispensable element to alleviate the effects of the crisis. Cuban farmers and city dwellers engaged in agriculture chose to experiment to maintain and increase the agricultural output. Thereby, they were able to guarantee the greater part of the basic food supply.

Also today, farmers' experiments and innovations prove to be important for Cuba's agriculture. Most Cuban farmers are involved in activities that can be called 'farmers' experiments'. However, there are large differences between experiments in terms of complexity, intensity, chronology, degree of participation and degree of consciousness. Some experiments and innovations might remain undetected because even the farmers themselves do not pay attention to small improvements in their daily farming practice. Farmers' experimental methods strongly depend on both their personal background and the kind and closeness of their relationships with scientists or extension agents. Those who are willing to present their experiments to a public audience generally use more sophisticated methods for conducting and evaluating them. These farmers often rely on the support from extensionists or scientists to elaborate a report and to prepare a presentation. Although some outstanding farmers conduct highly complex experiments by using scientific or semi-scientific methods, most of the experiments are simple and easily manageable. Farmers usually choose a pragmatic approach to experimentation and adapt or adjust the methods during the experimental process in order to achieve applicable results. Particularly, research-minded farmers are enthusiastic experimenters and are busily engaged in experimenting and trying out new things, whereas rather passive farmers avoid worrying about experimenting or else their experiments date back a long time. The outcomes of farmers' experiments primarily serve the purpose of improving a given current situation. Most farmers' experiments and innovations bear upon the local context.

Experiments and innovations are a fundamental part of farmers' working routine, independent of scientists' acceptance or support. They are natural ways of accumulating experience and enhancing the farmers' local knowledge. By experimenting, farmers improve farm management and contribute to agricultural development in the ways they already have been practicing for centuries.

Highlighted examples of farmers' experiments and innovations. In this section, we describe and analyze three cases of innovative farmers and present some of their most relevant results as evidence of their contribution to the Cuban AIS.

Casimiro and his multi-plough. Casimiro, a former policeman, lives in Sancti Spíritus province, in the center of the island. He owns a 10 ha farm and cultivates a variety of different crops and keeps livestock. Crop cultivation on his farm has always been labor intensive because of animal traction using either the American iron plough or the wooden Creole plough. Thus, reducing the workload was the farmer's motive to assess possibilities for building a plough on his own. Casimiro began to search for discarded but suitable iron parts that served him to build a new version of a plough for animal traction. During 3 years of experimentation with different shares he adapted the tool, step by step, to his farming conditions. Continuous observation and intermediary evaluation of the plough's performance in the field accompanied the experimentation process. Finally, Casimiro developed an iron plough with 28 different usages for tillage and weed control that helps him to save labor and costs by increasing the operating speed. Initially, the farmer was not aware of the potential of his multi-plough until a local MACAC representative took notice of his invention and started to promote its dissemination.

The farmer received Cuba's national innovation award at the Science and Technology Forum and participated in numerous national and international conferences where he presented his invention. With a strong holistic view of farming system management, Casimiro is widely known among agronomists and farmers not only for his multi-plough but also for his achievement in environmentally friendly farming. Many people visit the farm, including national and international delegations, governmental officials, agronomists, farmers and students. Up to date he has participated in 54 interviews for radio programs, TV programs and magazines, and often elaborates his own documentaries on his novel farming practices and philosophical views. His book about agroecology and family farming is an inspiration for other farmers and the Cuban society to better understand agroecology.

The irrigation system of Franchi. Franchi lives in Havana province and takes part in the urban agriculture movement. Before farming he worked in the construction industry. He owns a small plot of land within a small village and mainly produces cuttings and young plants that require abundant water. Buying an irrigation system would have been too expensive and very difficult to acquire. The visit to the farm of a colleague who owned an expensive irrigation system triggered his enthusiasm in finding a low-cost solution for irrigation. Franchi went through a long period of thinking and reflecting about the feasibility of a self-made irrigation system. Always convinced that building an efficient and cheap irrigation system would be possible, one day he had the idea that the

water itself has to open and close the water tap to save energy. He worked 2 years on the device using discarded materials until his efforts were finally converted into a much-noticed invention.

The main elements of the system are a recycled plastic bottle, recycled drip tubes from a hospital and a counterbalance based on hydraulic principles. Drip tubes determine the time to fill up the bottle. When the bottle is full it turns over and opens a water tap and thereby starts irrigating until the bottle is empty again. Duration of irrigation depends on the time the water requires to leak out and is controlled by drip tubes. When the bottle is empty it turns back to the original position, closes the water tap and starts filling again. This irrigation system works without electricity or fossil energy and requires a minimum of attendance, and thus supports the farmers' commitment to organic farming and sustainable agriculture.

Franchi obtained a patent for his irrigation system and participated in the Cuban innovation award forum. However, initially he faced skepticism from some prestigious scientists who underestimated the potential of a farmers' invention. Others, in turn, immediately recognized its great potential and supported the farmer to disseminate his irrigation system. Up to now he has received countless visitors including ministers, scientists and students, from Cuba and abroad. The farmer participated in numerous national and international conferences and traveled abroad several times to present his invention. Further, radio stations and TV stations broadcasted programs and newspapers and magazines published articles, on this experience. Research institutions and universities bestowed an honorific title upon him and occasionally invite him to give a talk.

Effective micro-organisms (EM) at Omars' farm. Omar lives in Varadero, Matanzas, a 2-h car journey east from Havana city in one of the most touristic areas of Cuba. He owns a farm, located some 15 km away from his home. As in the previous examples, farming was his response to the economic crisis after the collapse of the socialist system. He holds an academic degree in chemistry and worked as a teacher before starting his farm business. Omar has always been interested in learning new things and participated in a workshop for the elaboration of EM organized by the Experimental Station 'Indio Hatuey' (EEIH). The innovative farmer decided to produce EM on his own and obtained hermetic closable tanks. He started to look for basic raw materials that included micro-organisms in a wild area. Then he prepared a solid and a liquid mixture and filled the barrels for anaerobic fermentation. The application of EM led to very good results and they turned into an indispensable element on Omar's agroecological farm. After several experiments he was able to verify the positive effects. One experiment was the application of EM to assess the effects on rabbit nutrition. The farmer applied scientific methods to conduct and analyze his experiment. He is one of the very few farmers who know how to work on a computer and how to document his research process. Thus, researchers also acknowledge the scientific validity of his results. His conclusion was that the application of EM in rabbit production has a positive effect on the animals' health. Omar has already presented these and other results in scientific and semi-scientific conferences, in farmers' conferences and in the innovation award forum. He participates in the MACAC and uses the movement as a platform to disseminate his results. Omar is one of the most outstanding agroecological farmers in his province and therefore receives frequently national and international guests and maintains regular relationships with scientists and research centers.

The three cases provide evidence of farmers' experiments and farmers' participation in knowledge and innovation development. They indicate a general openness of the domestic AIS for participation of the civil society. These farmers and their innovations are widely known by other farmers and experts in Cuba. They are conscious about their experimental activities and spend more resources on experimenting than other farmers. However, such highly innovative farmers are a minority. Despite the fact that other farmers also develop and present notable innovations, few of them achieve the high publicity. Many farmers' innovations are valid for the specific local context but transfer to another context is difficult. Therefore, farmers' native capacity to experiment is the precondition to find own solutions for emerging problems and thereby to contribute to the domestic AIS.

Farmers' experiments and innovations and their linkage to agricultural institutions

Cuba's agricultural sector is highly regulated and institutionalized. Consequently, the agricultural institutions also influence farmers' experiments and innovations. The aim of the free-list exercise was to assess institutional influence on farmers' experiments and innovations. The interviewed experts mentioned 62 different institutions—or generic terms for institutions—that are known to influence farmers' experiments and innovations (Table 2). The most frequently mentioned institutions were ANAP and INCA.

Links between farmers and agricultural officials. ANAP represents private farmers and runs the MACAC, building on farmers' experiments as a core element of the whole movement. The high rank of INCA as a government body is an indicator of the success and importance of the PIAL. These two institutions determine the debate about farmers' experiments and innovations in Cuba to a large extend. However, with the method used to identify such a complex system linked to innovation, it is difficult in practice to accurately define the very nature of the institutions' influence on farmers' experiments and innovations. In many different forms, to some extent all the aforementioned institutions—whether governmental or not—have an effect on farmers' experimental processes and innovations. Many agricultural research institutions, farmers' organizations and development agencies, with

Table 2. Institutional influence on farmers' experiment and innovations. Institutions that are known by the respondents as influencing farmers' experiments and innovations ($n = 31$), including frequency of mention (f), percent of respondents (%), average rank (r) and Smith S (s).

Institution	Acronym	f	%	r	s
National Small Farmers' Association	ANAP	26	81	5.1	0.542
National Institute of Agricultural Science	INCA	24	75	5.4	0.499
Cuban Association of Agriculture and Forestry Technicians	ACTAF	19	59	7.3	0.329
Cuban Association of Animal Production	ACPA	18	56	7.6	0.273
Institute of Animal Sciences	ICA	15	47	7.2	0.269
Agricultural universities		15	47	7.9	0.159
Ministry of Agriculture	MINAGRI	11	34	2.5	0.305
Agricultural state enterprises		11	34	7.7	0.157
Ministry of Science, Technology and the Environment	CITMA	11	34	6.3	0.147
National Research Institute of Tropical Agriculture	INIFAT	10	31	4.4	0.235
National Research Institute of Plant Health	INISAV	10	31	6.3	0.188
National Research Institute of Tropical Roots and Tubers	INIVIT	10	31	7	0.184
Horticultural Research Institute 'Liliana Dimitrova'	IIHLD	10	31	8.5	0.155
National Center of Animal and Plant Health	CENSA	10	31	7.5	0.155
Soil Research Institute	IIS	8	25	5.9	0.154
Experimental Station 'Indio Hatuey'	EEIH	8	25	8.8	0.106
Pastures and Forages Research Institute	IIPF	7	22	7.7	0.128
Ministry of Higher Education	MES	7	22	5.3	0.105
Agricultural Delegation		7	22	6.4	0.103
People's Power Assembly	APP	6	19	4.5	0.103
Forum on Science and Technology	FCT	6	19	6.5	0.081
Rice Research Institute	IIA	5	16	9.2	0.086
National Association of Innovators and Rationalizers	ANIR	5	16	9.8	0.058
Agricultural Research Institute 'Jorge Dimitrov'	IIAJD	5	16	14.6	0.02
Research Institute of Tropical Fruit growing	IIFT	4	13	3.3	0.099
Granja Urbana	GU	4	13	7.8	0.065
Technical Youth Brigades	BTJ	4	13	11.8	0.038
Ministry of the Sugar Industry	MINAZ	3	9	2.7	0.075
Irrigation and Drainage Research Institute	IIRD	3	9	4.7	0.074
Swine Research Institute	IIP	3	9	9.7	0.055
Poultry Research Institute	IIA	3	9	10.3	0.052
Coffee and Cacao Research Station	ECICC	3	9	12.7	0.043
Cuban Communist Party	PCC	2	6	1	0.063
Research Institute of Agricultural Mechanization	IIMA	2	6	2	0.06
Tobacco Research Institute	II TABACO	2	6	9.5	0.042
Apiculture Research Institute	II APICOLA	2	6	11	0.038
Antonio Núñez Jiménez Foundation of Nature and Man	FANJ	2	6	5	0.036
Forestry Research Institute	IIF	2	6	11	0.034
Institute of veterinary medicine	IMV	2	6	14	0.031
Cooperative and Farmers Sector of the Ministry of Agriculture		2	6	4	0.028
Cuban Women Federation	FMC	2	6	7	0.027
Agricultural University of Havana	UNAH	2	6	10	0.02
Agriculture Polytechnic Institutes	IPA	2	6	14,5	0.004
Ministry of Economy and Planning	MEP	1	3	1	0.031
National Union of Arquitects and Construction Engineers of Cuba	UNAICC	1	3	4	0.023
Research Centre of Animal Improvement	CIMA	1	3	9	0.022
Unity of Extensionism and Research in Agronomic Science on sHolgin	UEICA-H	1	3	4	0.02
Centre for the Reproduction of Entomophagous and Entomophatogens	CREE	1	3	6	0.019
Swiss Agency for Development and Cooperation	COSUDE	1	3	8	0.017
Welthungerhilfe	AAA	1	3	9	0.015
Basic Unit of Cooperative Production	UBPC	1	3	8	0.014
Ministry of Foreign Investment and Economic Cooperation	MINVEC	1	3	7	0.014
ACSUR Las Segovias	ACSUR	1	3	10	0.013
Unity of Science and Technology	UCT	1	3	8	0.011
Norwegian Peoples' Aid	NPA	1	3	11	0.01
Center for Genetic Engineering and Biotechnology	CIGB	1	3	19	0.01

Table 2 (Continued)

Institution	Acronym	*f*	%	*r*	*s*
Program for Local Human Development	PDHL	1	3	12	0.008
Polo cientifico		1	3	4	0.008
Pastures and Forages Experimental Station 'Sancti Spiritus'	EEPFSS	1	3	10	0.006
Local Development Centre	CEDEL	1	3	10	0.006
Association of Sugar Cane Technicians	ATAC	1	3	7	0.004
Centre of Psychological and Sociological Research	CIPS	1	3	11	0.003

ANAP and INCA leading the way, encourage farmers to experiment and to innovate. Local staff members of centers for plant health, research institutions, ANAP offices and agricultural enterprises usually share a common understanding about the local production conditions with farmers. Further, the income gap and class distinctions are negligible and contribute to approximate farmers and advisors. Thus, the relationship is often characterized by trust and empathy. This is accurate not only for extension services but also for participatory research projects.

Participatory research. Participatory research in Cuba refers to scientific or semi-scientific research conducted in cooperation with farmers on their own fields. Farmers and their specific knowledge about the local environment are central actors in the research process. Participatory research is an upcoming approach in Cuba's agricultural science and builds on farmers' capacity and willingness to experiment. Increasingly, representatives of research institutes and the academic agricultural education sector invite farmers to participate in research projects or in the elaboration of MSc and PhD theses. The high density of educational institutions and the easy access to them favor the interaction between farmers and scientists or students, who often live in rural neighborhoods and therefore share a similar background with the farmers. Thus, most of the research relationships are characterized by trust and mutual understanding. Farmers' participation mainly includes technology assessment or feasibility evaluation of innovations introduced from outside, e.g., new varieties, organic fertilizers, erosion control methods, etc.

Probably, the most successful example of participatory research in Cuba has been the Participatory Plant Breeding Project (*Proyecto de Fitomejoramiento Participativo*, FP) launched by INCA in 1999. INCA's scientists offered seeds to farmers and encouraged them to conduct experiments, to assess the suitability of different varieties for specific farming conditions and to follow their own perceptions of what sustainability is. In 2007, the FP project merged into PIAL, expanding the original concept. At present, the project encourages farmers to experiment on any topic of interest and pays more intense attention to socio-economic and environmental issues involved with agriculture (i.e., farmers' empowerment, gender issues and climate change). This program has been successful in engaging practitioners looking for their own solutions with the support of project staff members at each so-called Center for Local Agricultural Innovation (*Centro Local de Innovación Agropecuaria*, CLIA). It strengthens individual farmers and cooperatives willing to experiment with new agricultural technologies or to innovate on their own and facilitates widely the dissemination of their own results. PIAL is a development project financed and supported by international development agencies with INCA as the local counterpart that is linked to a broad network of institutions. Four main principles have been basic to reach the objectives: access to biological and technological diversity, farmers' empowerment and decision making, transferability of results and acknowledgement of recognizable environmental and socio-economic achievements.

Other institutions with national impact on agricultural innovation, which have emphasized farmers' participation in their research projects, are, for example, INISAV, the National Institute for Basic Research on Tropical Agriculture (*Instituto de Investigaciones Fundamentales en Agricultura Tropical*, INIFAT) or the National Research Institute for Tropical Roots and Tubers (*Instituto Nacional de Investigaciones de Viandas Tropicales*, INIVIT). Most of the research projects include an on-farm research component with different levels of farmers' participation, depending on the researchers' and the farmers' willingness to collaborate. The role of farmers in such projects focuses on the assessment of technologies and practices in their own farms as well as participation in group discussion and local, national and international events.

Institutionalizing farmers' experiments and innovations

By experimenting and innovating, farmers contribute to knowledge development. Knowledge exchange encounters provide opportunities to integrate farmers' experiments and innovations into Cuba's AIS and thereby are conducive to mutual learning among the diverse actors. Knowledge exchange encounters allow farmers to communicate their experiences to other farmers, the scientific community and to extension agents.

The farmers' purpose is food production to sustain family livelihood. Thus, experiments and innovations are usually a side effect of farming activities, and few farmers are conscious and active experimenters who are willing to spend additional resources on experimentation. Nevertheless, experimenting is a key element in food system

functioning and adaptation to change. Incorporation of farmers' knowledge and expertise into formal research agendas leads to organizational learning and institutional benefits. With farmers' participation, the applicability of research results increases and the immediate social impact of research projects is enhanced. Evidence of the rapport among researchers, academics and extension agents is that all respondents who worked directly with farmers could mention at least one farmers' innovation and were open minded toward farmers' contribution to the AIS. This suggests an encouraging climate toward the institutionalization of farmers' experiments and innovations and that a great part of the scientific community in Cuba acknowledges farmers' contributions to knowledge and innovation development.

The Forum of Science and Technology. The long history of ambivalent relations with the US government and the US trade embargo triggered the first tendencies to liberate Cuban industry from the US Ernesto Che Guevara founded an association to organize the production and reproduction of spare parts. Later, and based on Guevara's attempts, the National Association for Innovators and Rationalisers (*Asociación Nacional de Innovadores y Racionalizadores,* ANIR) was founded to represent all Cuban citizens who successfully innovated, invented or contributed to rationalize production.

For many years the participation of the civil society has been part of Cuba's innovation policy. The Forum of Science and Technology, created in 1983 by Fidel Castro, has been for years the best-established movement for knowledge exchange and institutionalization of farmers' innovations. All Cuban citizens are encouraged to participate and to present their innovations or inventions to a wider audience. A committee of experts awards relevant innovations in 13 different sectors, including food and agriculture. The forum starts at the local level and ends at the national level. Institutions of the agricultural sector (e.g., INCA, ANAP, ACTAF, agricultural state enterprises, etc.) organize their own forums and select the most relevant works to be presented at the higher level. The various forums for the food and agricultural sector provide platforms for farmers, farm workers and agricultural scientists to present their experiments, innovations and inventions. The municipal offices for statistics collect all awarded contributions and the CITMA recently started to compile them on a central database. ANAP is in charge of the organization of the forum for the private farming sector and the Agroecological Farmer-to-Farmer Movement has given rise to a high degree of agroecological farmers' experiments and innovations presented at the forum.

In case of inventions, the author has to apply for a patent at the Cuban Office for Industrial Property (*Officina Cubana de la Propiedad Industrial*, OCPI). If the invention is developed at the place of employment, the government guarantees the author's property rights but reserves the right for commercialization. Otherwise, the person who develops the invention holds the right to inhibit commercial use. Non-commercial use is allowed anyway.

The biodiversity fairs. An interesting platform for knowledge exchange is the so-called 'biodiversity fair' which was initially organized by staff members from INCA working on the FP project. Farmers who experimented with seed varieties assembled to exchange seeds and experiences. The fairs quickly became social events called 'biodiversity festivals', where children, women and other social groups got involved. It included traditional singers, competitions of dishes made with novel bean or corn varieties and other traditional foods. Participants accepted the fairs so well that during the course of the project, farmers started to organize fairs on their own. Even if some fairs are organized by farmers themselves, usually scientists and extension agents participate and provide support. Like this, the project became a process with its own dynamics and led to about 40,000 beneficiaries all over Cuba. Staff members usually document the fairs and local media occasionally takes up the topic for publishing.

Farmers' participation in conferences. Farmers' participation in national and international conferences is a promising approach for institutionalizing farmers' experiments and innovations. The main purpose of inviting farmers to conferences is to facilitate knowledge exchange between them and scientists. Several Cuban institutions organize conferences with farmers' participation on a regular basis. ANAP and ACTAF organized conferences where farmers' presentations—mostly based on their experiments and innovations—made up over 80% of the total. Their participation included poster presentations, panel discussions or even as keynote speakers in plenary sessions. The organizing committees compile farmers' experiments and innovations and publish print or digital versions of the proceedings[53].

Characterization of Cuba's AIS. Cuba's AIS is embedded in a contextual framework that shapes the properties of the system and the nature of innovation processes (Fig. 1). Cuban policy provides the legal basis for agricultural institutions to facilitate farmers' experiments and innovations. Agricultural institutions, whether scientific or non-scientific, are embedded in a network of interconnected relations with each other. Relations are based on material exchange, such as funding, and non-material exchange, such as services or information. Socio-economic conditions refer, for instance, to resource scarcity, the US trade embargo or income levels. The bio-physical context of the island includes weather and soil conditions, the duration of the growing season but also droughts, heavy rainfalls or hurricanes. These conditions influence farmers in their decision making and their scope of action, and potentially trigger self-determined experimentation. Innovation is the core element of the AIS, interconnecting knowledge development, dissemination and appropriation. In other words, an innovation is the vehicle that transfers new knowledge from one actor in the AIS to another. Farmers and scientists are involved in

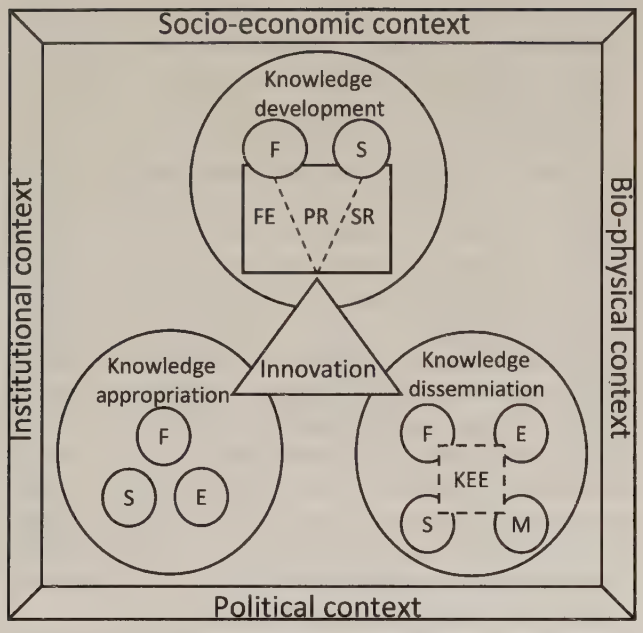

Figure 1. Cuba's agricultural innovation system. F, Farmers; S, Scientists; E, Extensionists; M, Media; FE, Farmers' Experiments; PR, Participatory Research; SR, Scientific Research; KEE, Knowledge Exchange Encounter.

knowledge development. Farmers conduct informal experiments on their farms and scientists conduct formal research in laboratories or experimental plots. Both increasingly work together in participatory research projects building on farmers' local knowledge and their native capacity to experiment and innovate. Informal, formal and participatory research potentially lead to innovations. Knowledge exchange encounters play a key role in terms of dissemination and institutionalization of farmers' innovations. Extension services, media, scientists and farmers themselves actively disseminate agricultural knowledge and innovations. Efficiency of dissemination strategies and accessibility to information sources influence knowledge appropriation. AIS stakeholders use novel knowledge to put it into practice, to multiply it or as a starting point for further formal or informal research that can result in further innovation. The end-users of innovations manage a specific amount of new knowledge, whether embedded in a technology or not, and integrate it into their existing local knowledge base. This integration gives rise to a new, hybrid and evolving form of knowledge.

Discussion

Since the Cuban revolution succeeded, the government has aimed at establishing a society in which marketability and profitability of innovations are of secondary importance. The trade embargo soon led to first initiatives to sever the Cuban economy from the US The creation of the National Association for Innovators and Rationalisers and the foundation of the Forum of Science and Technology have been crucial milestones in the process of socializing knowledge and innovation development.

Education has been free of charge and compulsory up to an age of 16 and has led to the high literacy rate of more than 95%. The average level of education is the ninth grade and more than half a million Cubans hold an academic degree[54]. The establishment of university centers in municipalities has enhanced educational chances and has contributed to decrease the gap between scientists and the working class. These educational strategies have reinforced farmers' innovative capacity and provided favorable conditions to open science for the public.

Thus, political leaders appeal to the citizens to take on a responsibility for technological progress and development. Research issues are first defined by local citizens and then discussed by local research institutes and universities. Ministries take up the proposals, evaluate and prioritize them. That approach guarantees a high level of individual engagement in the decision-making process for research priorities[55]. A sense of public ownership for research has developed. The result is a new ethic of science that is in contrast to the capitalist approach. In capitalist systems, scientific research is funded with the wealth of the public but research institutions demand the supremacy of knowledge. In addition, the private sector increasingly funds projects and tries to commercialize research findings for maximization of profits and often at the cost of farmers. Capitalist systems disregard social participation but on the contrary favor the concentration of knowledge and innovations in the hands of a minority[56]. The results of this study show that Cuba's government has chosen a more participatory approach to research and development than capitalist countries have done. The political decision makers, pursuing socialist ideals, recognized the social dimension of science and technology and have made innovation development a public concern. The socialization of knowledge is conducive to a more equitable society. However, even if innovation development is socially founded, hierarchical structures sometimes overshadow participatory approaches.

The collapse of the socialist block triggered the urgent need to react to resource constraints and enhanced the tendencies to achieve technological autonomy and food sovereignty. The agricultural policy, research and extension services were forced to adapt to a new situation. The economic crisis was associated with fundamental changes in the agricultural sector that concerned the partial transformation of state farms into Basic Units of Cooperative Production (*Unidad Básica de Producción Cooperativa*, UBPC) and into New Type State Farms (*Granja Estatal de Nuevo Tipo*, GENT). Further, the government distributed farm land in usufruct to peasant farmers, encouraged local and small-scale food production and supported the rise of urban agriculture. All these changes were accompanied by an increase in autonomy for on-farm decision making[57]. With more autonomy, farmers' willingness to assume

personal responsibility increased. Individual initiatives led to informal experimentation and eventually to the development of appropriate technology. This study reveals that the historically caused changes in the agricultural sector called for coping strategies. These strategies were based on a combination of the government's commitment to social participation in the domestic AIS and farmers' potential to experiment and innovate.

Apart from direct policy measures to facilitate social participation in the AIS, the Agroecological Farmer-to-Farmer Movement and the Program for Local Agricultural Innovation additionally have upgraded farmers' experiments and innovations in Cuba. The incorporation of the ANAP into the transnational movement La Via Campesina strengthens the importance of agroecology and the farmer-to-farmer methodology for peasant movements on an international level. ANAP has promoted agroecology for more than 10 years and is therefore qualified to coordinate the Division for Sustainable Peasant Agriculture within La Via Campesina. One of ANAP's tasks is to identify, study, analyze and document the most advanced and positive experiences of agroecology. The aim is to share the lessons with other member organizations all over the world[58]. Thus, the potential of farmers' experiments and innovations, as an integral part of the Agroecological Farmer-to-Farmer Movement, are in line for widespread appreciation.

Conclusion

Opportunities for knowledge dissemination and exchange shape the nature of Cuba's AIS. Personal interaction between the stakeholders and encounters for open discussion favor knowledge transfer. Cooperative meetings, workshops, conferences and the Forum of Science and Technology itself are crucial platforms that facilitate the communication of farmers' experiences to the public and further contribute to institutionalize them. As these events start on a local level and sometimes even include the international level, they help improve the spread of innovations and new agricultural knowledge among farmers, extension agents and scientists. Hence, the Cuban example demonstrates how farmers' experiments and innovations can be integrated into functional AIS in such a way that farmers' innovative capacity is fully recognized.

Cuba's administrative and institutional structure provides several platforms for farmers to exchange and spread knowledge, though on occasion the lack of flexibility of such platforms lowers the diffusion of innovations. Although agricultural extension and the media play a crucial role for knowledge dissemination, the potential end-users of agricultural innovations are often unaware of the results achieved by formal and informal research. The respondents claimed that the diffusion of innovations mostly depend on local initiatives and mainly remain a farmers' domain. Thus, the personal communication networks are crucial for dissemination of knowledge and innovations.

The Cuban example illustrates how raising farmers' participation helps to build up a socially based knowledge pool and leads to agricultural development. Although farmers' participation in agricultural research and development is an upcoming approach, the top-down conventional mindset still prevails among scientists, extension agents and policy makers. Providing a proper environment and policy incentives for farmers' active participation, and recognition of farmers' own experimentation and innovation capacity, will help them develop their full potential within the AIS. Political commitment to research, education and social participation in agricultural development is an effective way to upgrade the efficiency of the AIS. However, it should be made clear that a national policy can only build the general framework for the integration of farmers' experiments and that further integration will depend on local decision makers, who directly interact with farmers. Therefore, agricultural decision makers should actively involve farmers in knowledge and technology development.

The innovative capacity of individuals and groups is a powerful element of AIS that can contribute to the system's resilience. Favoring farmers' experiments might help to increase the adaptive capacity of farmers. The heterogeneity of roles and interactions of the different stakeholders within the AIS determines the capacity to respond to external changes and therefore can help to build systems' resilience.

Acknowledgements. The authors want to thank the Austrian Science Foundation (FWF) for financing the project 'Organic Farmers' Experiments', including its funding of field research in Cuba. The field work in Cuba was done thanks to a student visa under an official agreement between the University of Natural Resources and Life Sciences (BOKU), the Experimental Station 'Indio Hatuey' (*Estación Experimental 'Indio Hatuey'* EEIH) and the National Institute of Agricultural Sciences (INCA). This research would not have been possible without the intensive support from our Cuban colleague Humberto Ríos. We also thank Elena Sanz Soro, May Ling Chan, Eduardo Freire and Racheli Ninio for the inspiring discussions about the subject of our paper.

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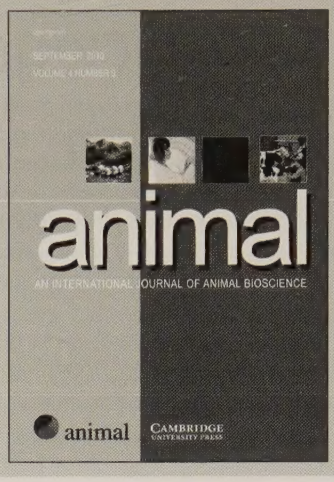

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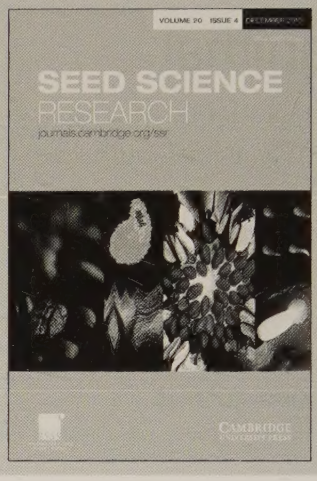

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The importance of seeds to propagation, food, biofuel and biodiversity is of increasing interest and therefore submissions on seed genetics, seed biotechnology, seed treatment and seedling establishment are especially encouraged if they are novel and 'seed driven'.

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2. Brink, R.H. Jr, Dubach, P., and Lynch, D.I., 1960. Measurement of carbohydrates in soil hydrolyzates with anthrone. Soil Science 89:157–166.
3. Greenland, D.J., and Szabolcs, I., (eds). 1994. Soil Resilience and Sustainable Land Use. CAB International, Wallingford, UK.
4. Arshad, M.A., and Coen, G.M., 1992. Characterization of soil quality: Physical and chemical criteria. American Journal of Alternative Agriculture 7:25–31.
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Renewable Agriculture and Food Systems

Volume 26 Number 4 December 2011

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